SPECIAL ISSUE THE STATE OF INNOVATION

TECHNOLOGY REVIEW

JUNE 2002

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THE YOUNG INNOVATORS WHO WILL CREATE THE FUTURE

TR100

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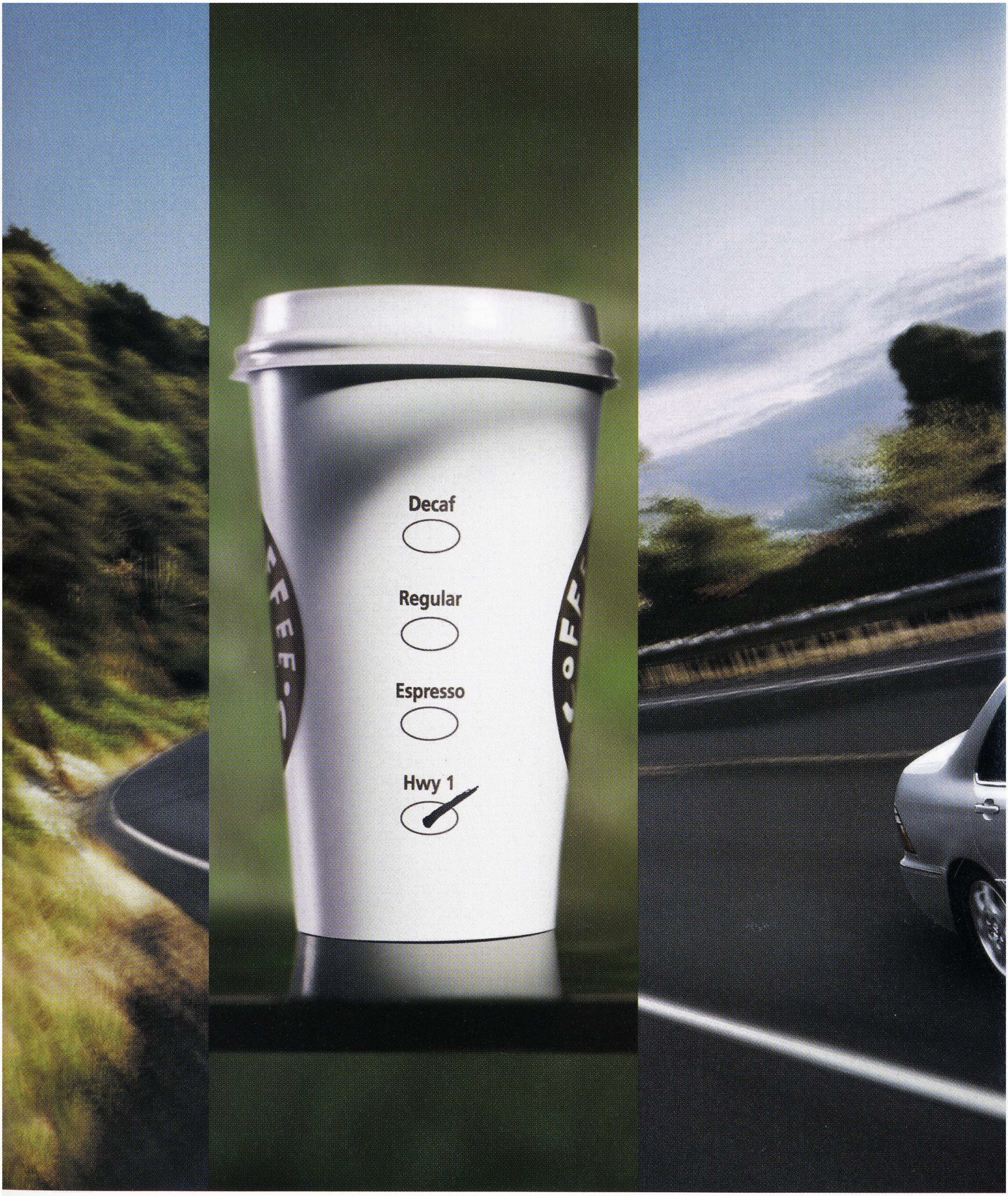
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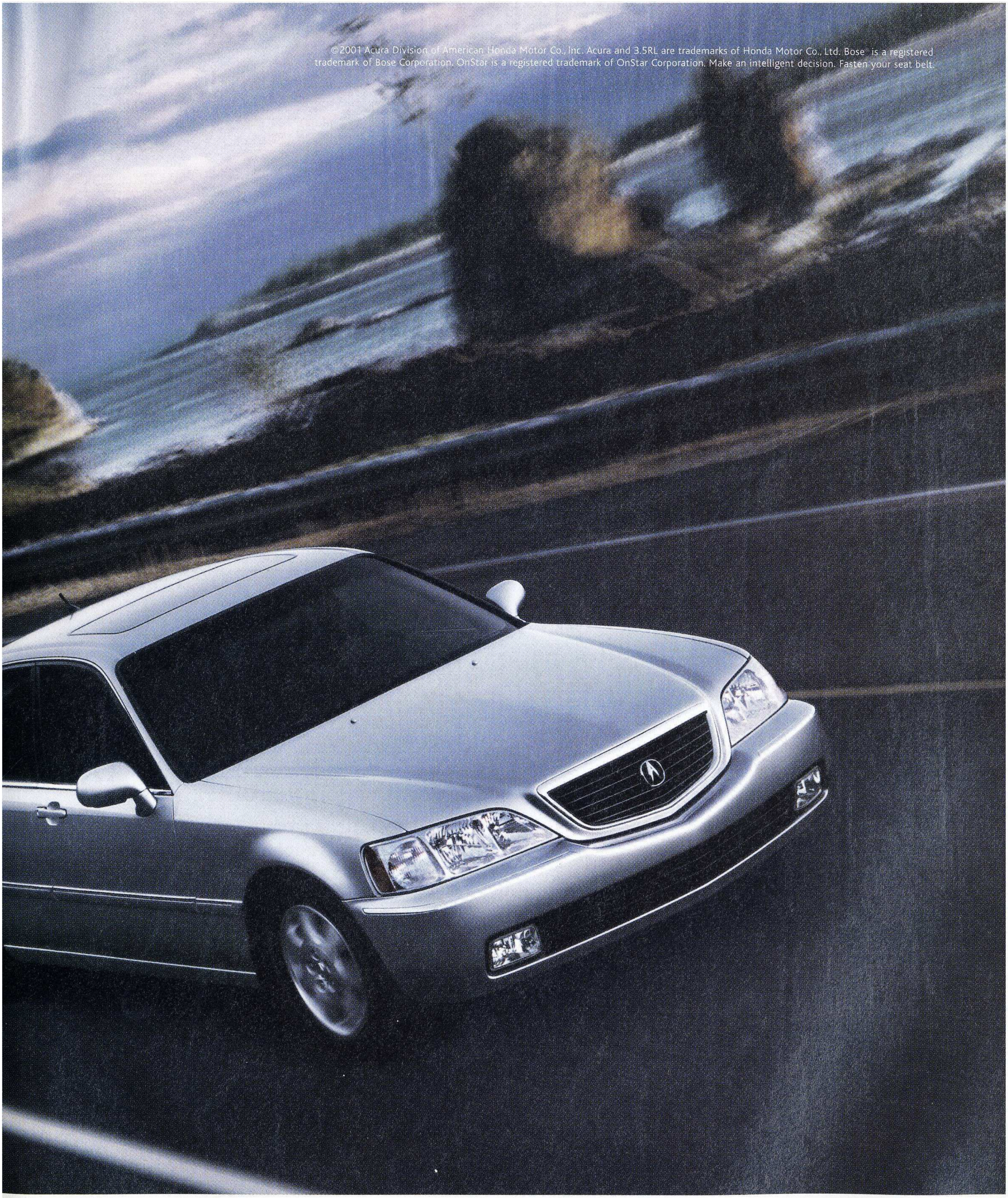

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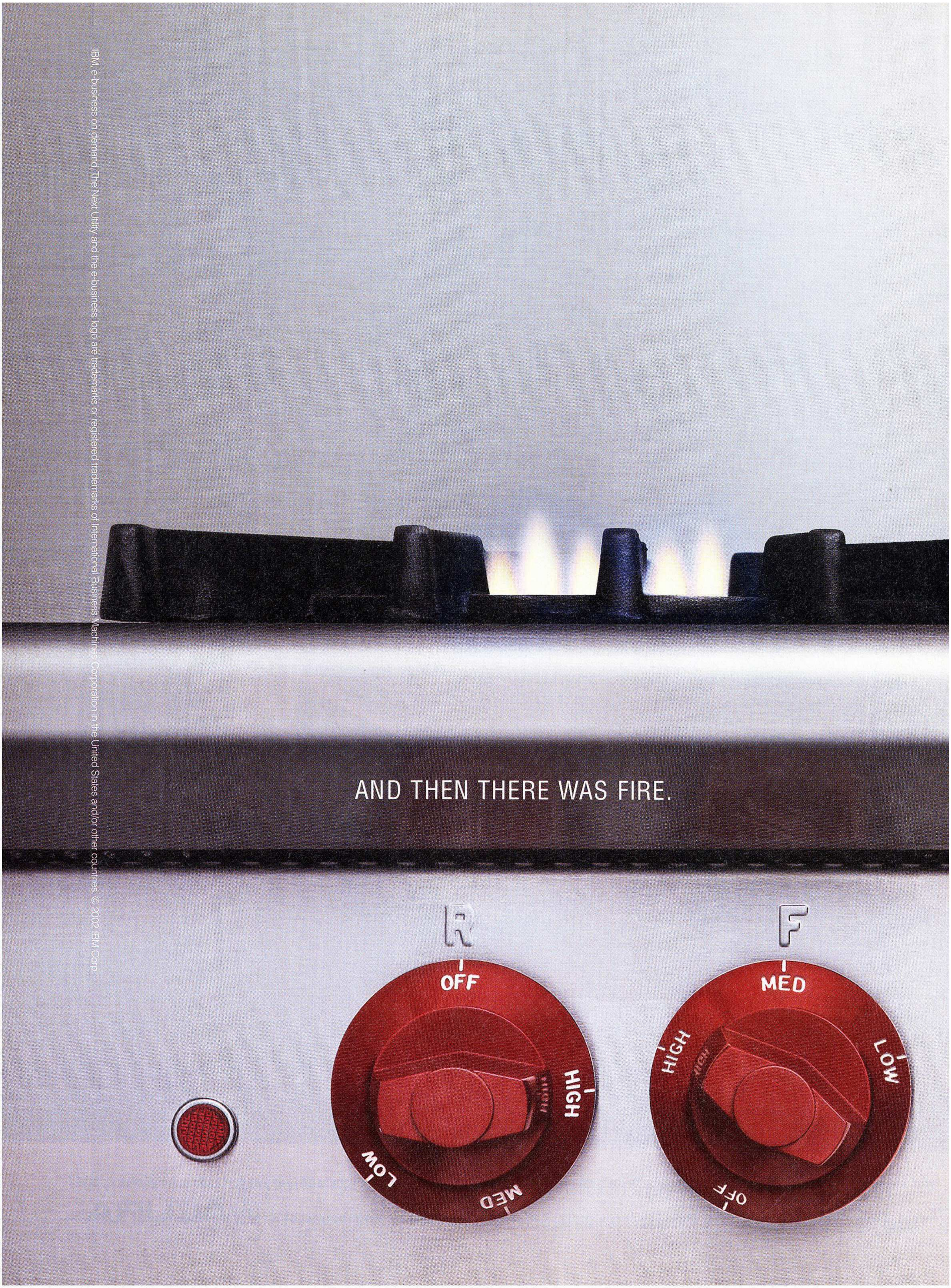
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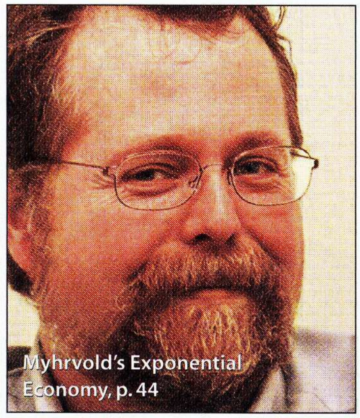

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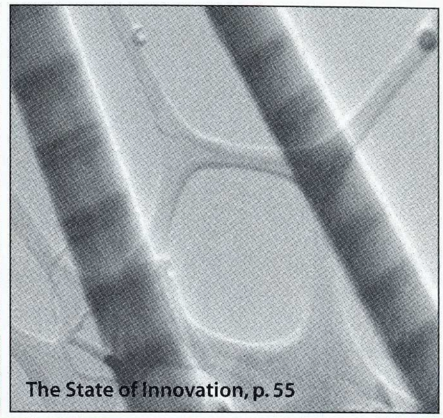

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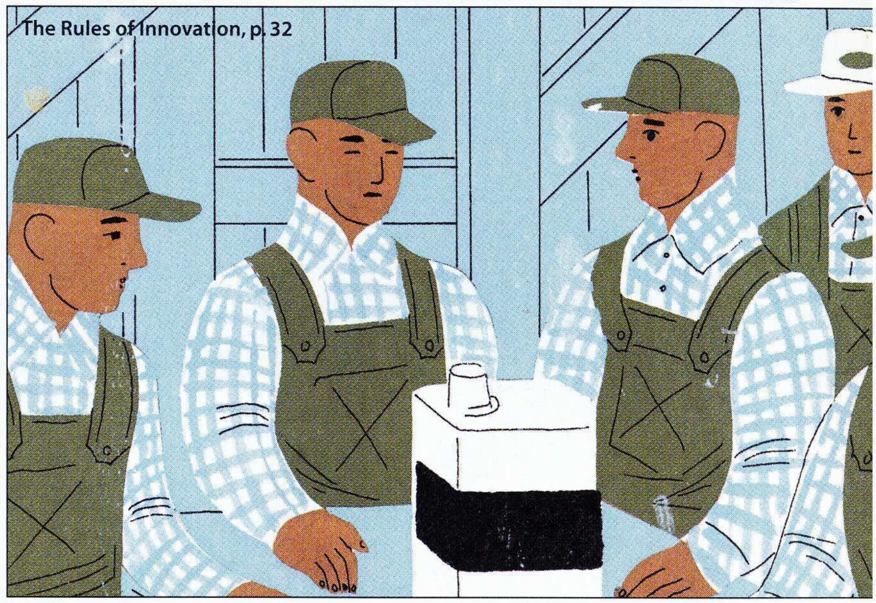

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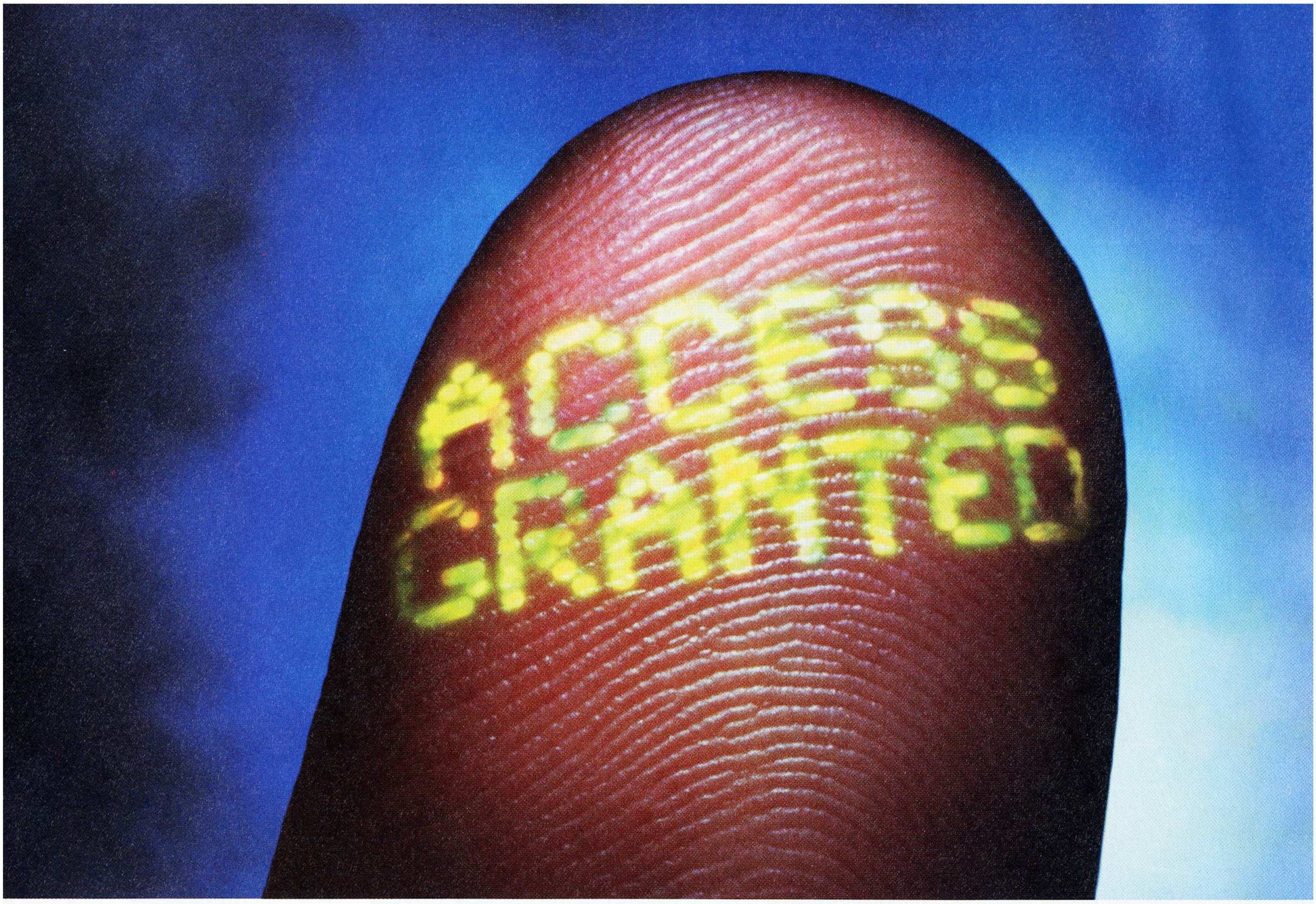
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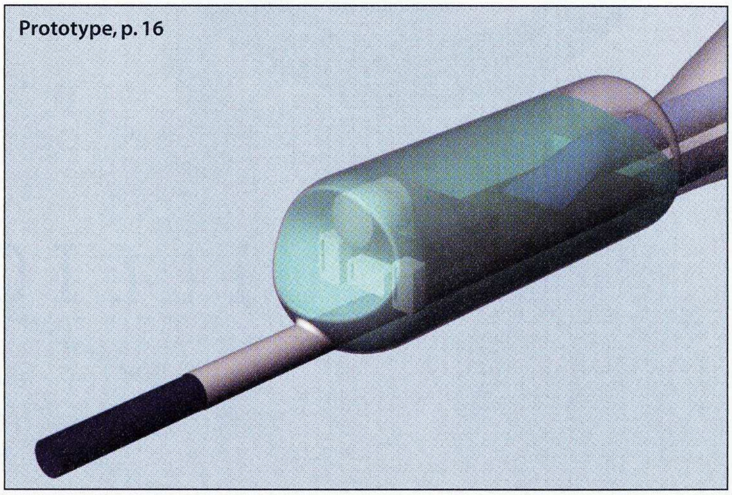

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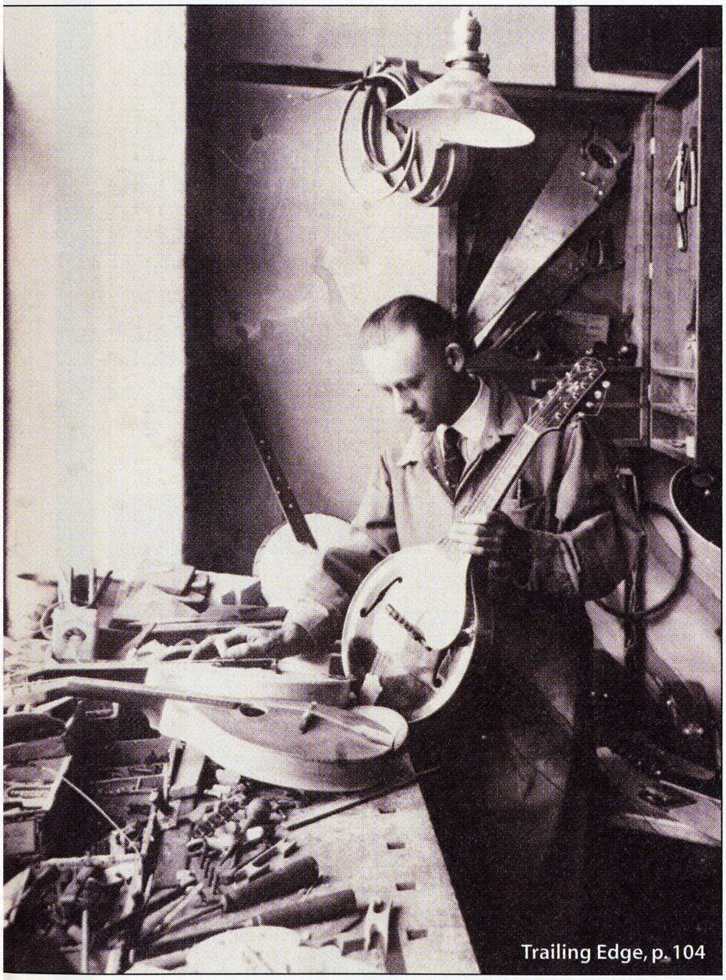

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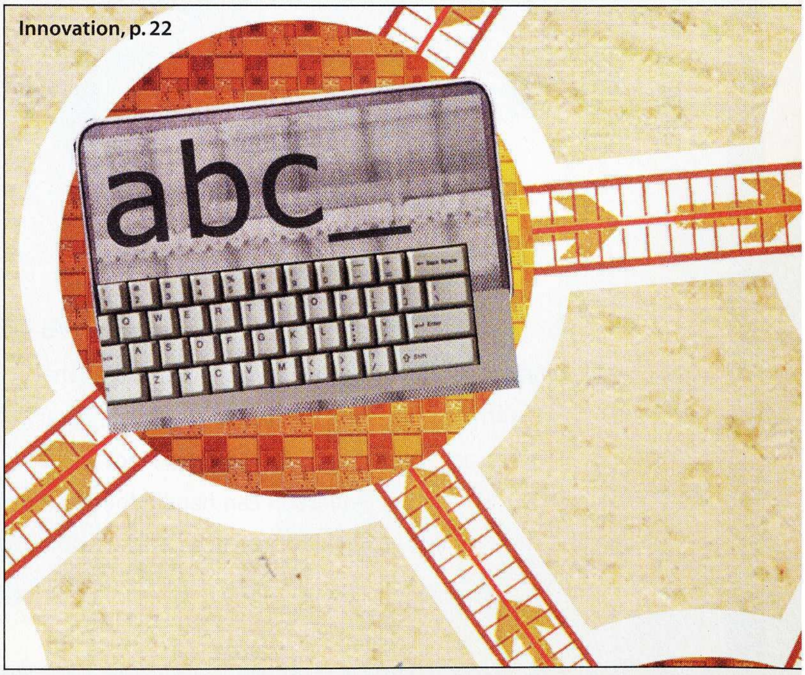

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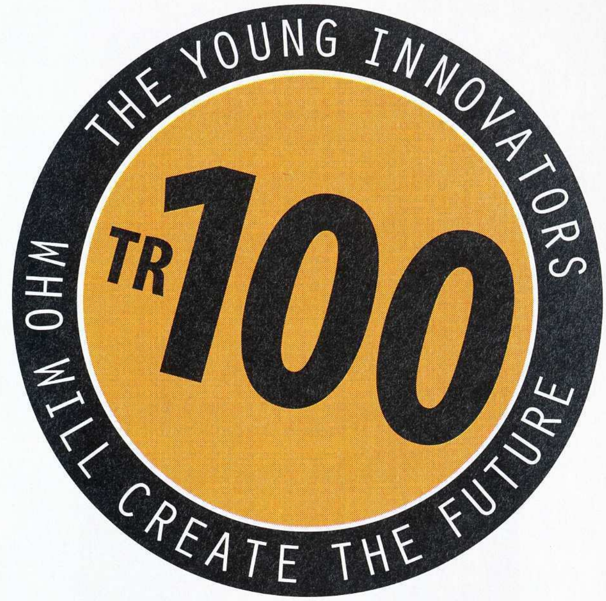

ON THE WEB

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▪ Search through a collection of biographies, research and links related to this year's finalists.
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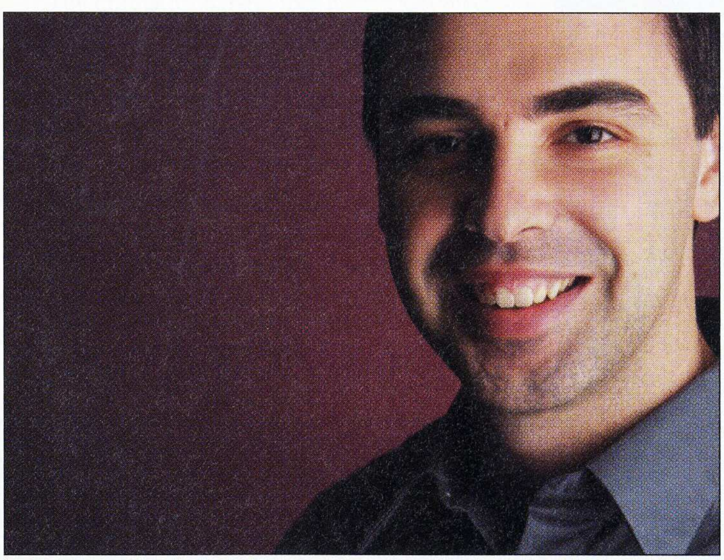

THEY MAKE THE FUTURE HAPPEN

What does it take to make the future happen? Brilliance, of course. But there are plenty of brilliant people in the world and yet so few who finally make a difference. What's the additional required element? Hmmm…not easy to say. Perhaps there isn't a single word for it in English, although in our innovation economy there certainly should be. It's the capacity to translate a remarkable conception into an equally remarkable reality, adjusting to the demands imposed by a constantly shifting environment along the way. Practicality? Yes. Mental toughness, the kind coaches preach to athletes? Yes. Presentation and marketing skills? Quite likely. It's a constellation of qualities that enables ideas to make their way out of the laboratory and into the world, the only place they can really have an effect. And it's what we looked for in selecting the TR100 for 2002.

This is the second time we've picked a promising group of young innovators (under 35 as of Jan. 1, 2002) and presented them in a special issue of *Technology Review*. The first group, showcased in our November/December issue in 1999, represented an outstanding assemblage of talent. When we brought them together, here at MIT, they instantly recognized each other, as peers do, and began busily networking, resulting in some collaborations that are still ongoing. Some of the things that have happened to the first TR100 are profiled in a piece that begins on page 98. The period between late 1999 and now has been a tumultuous one for our economy and our society: some of the initial TR100 have struggled as the times changed; others have risen straight to the top.

The dramatic changes that have taken place since we picked the first group of young innovators dictated that we shouldn't simply replicate what we did the first time. One of those changes has been the death of the "new economy." *Technology Review* was never a big fan of the new economy, and the first TR100 reflected our preference for substantive advances in technology, as opposed to the latest Web-centric hype. But in this incarnation of the TR100 we've made that preference even more explicit by taking as our theme the transformation of existing industries and the creation of new ones.

Each member of the TR100/2002 was picked with this theme in mind. The screening process began more than a year ago as we assembled the largest possible pool of serious candidates. We asked you, our readers, to nominate people you thought were worthy; we canvassed our distinguished panel of judges (who are listed on page 97); the editors here on Main Street in Cambridge pitched in with the names of young innovators they'd come across over the last two years; and we relied on the tremendous diligence of our project editors Mark Fischetti and Brad Stenger.

Having filled the pot, we stirred it. The editors vetted candidates, and then we invoked the expertise of our judges. In almost every case, we agreed with the judges. Although we didn't apply formal procedures to ensure diversity, I'm happy to report that we have more women in this group than we did in the first TR100, and stronger representation from outside the United States—both trends that help us to better represent the true global distribution of innovation.

What kind of work do our winners do? We looked for areas where we believe the pace of innovation is quickening and the technology landscape will look quite different in a decade or so. Those areas include the core of our editorial franchise: biotechnology (and medicine), information technology (broadly conceived) and nanotechnology (along with materials science). But we have also selected candidates who work in energy and transportation, because we feel strongly that those industries will, over the next decade, be remade by the work of the group we've selected—and by others coming along right behind them.

For the second time, *TR* has selected a remarkable group of innovators under 35. This year's theme: transforming existing industries and creating new ones. Watch them do just that.

We hope you will enjoy the 100 profiles we've prepared for you, beginning on page 65. But the rest of this special issue is just as enticing. The lead article is a piece by Clayton Christensen of Harvard Business School, author of *The Innovator's Dilemma*. Christensen previews his next book, setting forth the four rules that he thinks will help innovators escape the trap he described in his first book. Daniel Kevles of Yale University tells us why human cloning is on its way—like it or not. In an incisive Q&A with editor at large Robert Buderi, Nathan Myhrvold—once Microsoft's resident research genius—explores his plans to encourage innovation in far broader fields, beyond Redmond. We've also profiled the "state of innovation" in four of the key areas that contributed members to this year's TR100: infotech, biomedicine, nanotech and transportation. To round things off, we've given you a survey of "10 Technology Disasters," drawing critical lessons from them for today's innovators.

If you wish to go deeper into the TR100, our Web site offers more information about each of the winners, with links to their companies and scientific publications (www.technologyreview.com/tr100/feature). By following those links, you will find more detail about what each of these promising young innovators is doing. That way, you will be positioning yourself to track them as their work begins to transform our world. Predicting the future is always a hit-or-miss affair, but I am confident that keeping an eye on the TR100 will give you an insider's view on where technology is headed. —*John Benditt*

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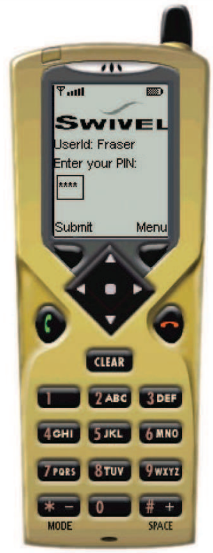
PIN ON THE GO

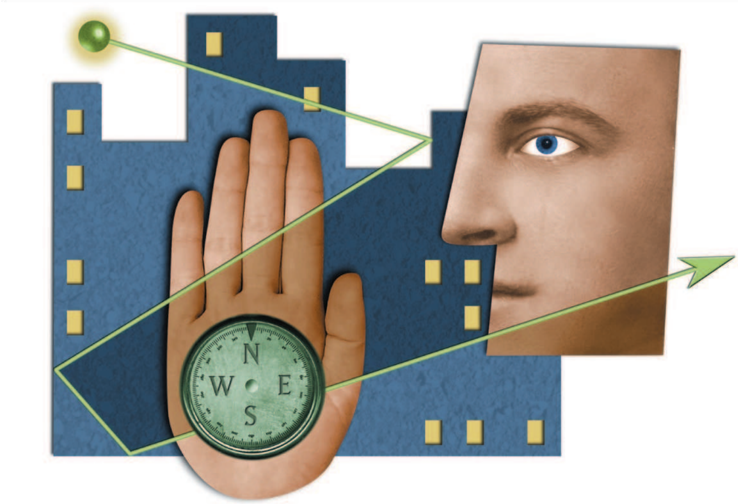
If you worry that one day someone will steal your credit card number, protection may be on the way. Swivel Technologies of Knaresborough, England, has developed a credit card system that generates a fresh, unpredictable number for every transaction.

A user who registers with Swivel receives a four-digit personal identification number that can be used on a cell phone, computer, personal digital assistant or any other device equipped with Swivel's software. When this PIN is entered, the Swivel software generates a random 10-digit sequence that, in combination with the PIN, produces a unique one-time code; that code is transmitted to Swivel's server, which authenticates the transaction. Interception of the wireless signal would do a would-be thief no good, because the transaction code is generated anew each time. The Swivel system can be used with existing digital phones as well as those based on higher-bandwidth "third-generation" (3G) wireless technology. The patented system should be commercially available within two years.



ORIGINAL PROOF

With today's sophisticated document scanners, color printers and photocopiers, counterfeiters can easily forge all sorts of official paperwork—even money. Researchers at the Palo Alto Research Center have developed a way to protect computer-printed documents from illicit duplication. The system puts a random pattern of bumps and ridges on the rollers that move paper through an ink-jet or laser printer. The rollers emboss the paper with a unique pattern, invisible to copiers and scanners, which is recorded in a database. Anyone needing to authenticate a document would run it through a special device that reads the embossing, then query the database. Inventor Tom Berson says PARC is looking for a company to license and commercialize the technology.



LOCATION, LOCATION, LOCATION

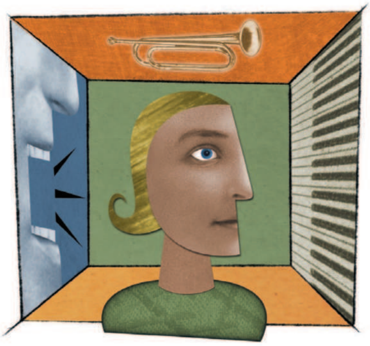
Anyone who's tried it knows: the Global Positioning System works great when you're finding your way back from the middle of nowhere. But in a crowded city, where satellite signals ricochet off buildings, the system isn't terribly accurate; relying on GPS may land you in the Hudson River rather than at the Empire State Building. South San Francisco, CA-based startup Enuvis has developed software that helps GPS cope with the urban jungle. Called UrbanGPS, the software includes algorithms that help units lock onto weak satellite signals, differentiate true signals from echoes and process more of the satellite signal faster. Enuvis has tested the technology in some of the world's toughest cities—including Tokyo, Seoul and San Francisco. Receivers using UrbanGPS were twice as accurate as standard units, giving position within 20 to 40 meters, according to company president Michael Kim. The company is marketing the software, which can run on simple microprocessors, to cellular carriers looking to provide location-based services such as enhanced directory assistance, traffic information, personal navigation and emergency assistance.

STEADIER SURGERY

Even the world's steadiest surgeons can't avoid minuscule, involuntary hand motions. Researchers at Carnegie Mellon's Robotics Institute have developed active surgical instruments that can sense and compensate for these tremors. Tiny motion sensors on the tip of each instrument track its location, relaying the information to a computer. Software analyzes this data to distinguish intentional hand movements from the higher-frequency tremors. The computer sends a signal to piezoelectric actuators within the instrument's handle that cancel out unwanted motion.

The researchers have shown they can cut the size of surgeons' tremors in half, says project leader Cameron Riviere. These auto-steadying instruments should be cheaper and simpler to master than alternatives such as an electronically manipulated robotic arm. Within a year, the University of Southern California's Retina Institute will test the devices in real surgery; several companies have expressed interest in commercializing the technology.

COURTESY OF DEBRA TOBIN (STEADIER SURGERY); JOYCE HESSELBERTH (ILLUSTRATION); COURTESY OF SWIVEL TECHNOLOGIES (PIN ON THE GO)



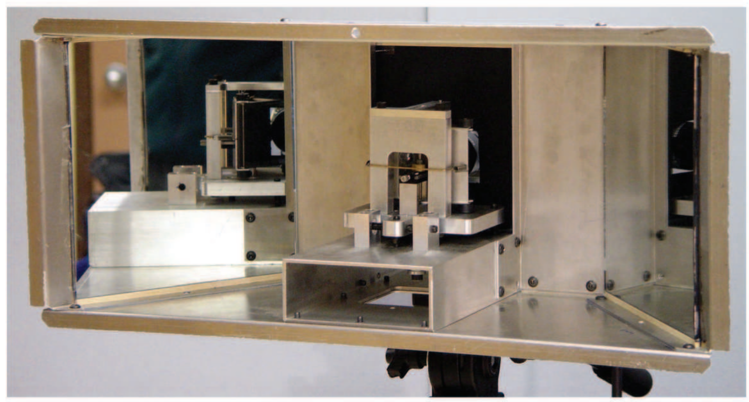
SOUND ALL AROUND

Three-dimensional sound effects—like a voice seemingly moving from behind you to in front of you, or coming from far away—are common features in video games and could begin to enhance otherwise flat business presentations. Scientists at Siemens Corporate Research in Princeton, NJ, have developed Web-based software that applies myriad tricks—such as reverb and sound-muffling—to audio files to create such effects; it also streams the finished product, so users of handheld devices can hear it through their headphones. The Siemens approach requires none of the laborious programming that sophisticated audio manipulation usually entails; it works by adding a few new extensions to an existing Web standard known as the synchronized multimedia integration language. To hear the 3-D audio results, the listener simply goes to the Web site where the file is stored. A prototype is complete, says project manager Stuart Goose, but Siemens has not stated any plans for commercialization.

FLATSPEAKERS

Roy Kornbluh at SRI International in Menlo Park, CA, is developing the loudspeakers of tomorrow—which look a lot like the plastic wrapping that the speakers of today come packaged in. Kornbluh treats silicone with an electrically conductive grease that makes it expand and contract when charged. Sending electric signals through a thinly stretched sheet of the stuff causes vibrations, thus generating sound waves.

Light, flat and flexible, the silicone speakers could be applied to surfaces that conventional speakers would be too bulky for—for instance, they could line a car's interior roof. And because sheets of silicone are easy to fabricate, doubling or tripling their size should add only a few cents to their production cost; eventually it may be possible for them to cover entire walls in your house. SRI says it has already built speakers that can passably reproduce a symphony; a version that matches today's highest-fidelity speakers is probably about three years away.

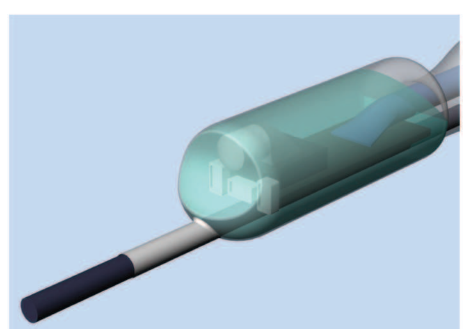


3-D IN ONE

All Olivier Zanen wanted was a cheap and easy way to take 3-D pictures of insects during flight, without having to rely on multiple cameras or expensive laser scanners. So the Cornell University entomologist developed his own technology—a mirror-based contraption that lets a single handheld camera produce 3-D pictures. Zanen's imager fits like an adapter onto a standard video camera; its two pairs of mirrors *(above)* capture both left and right views of an object. The complementary images are then downloaded to a PC, where software translates them into a 3-D reconstruction of the object. Zanen cofounded Synceros in Ithaca, NY, to commercialize the technology for an application less esoteric than insect photography: face recognition. Standard face recognition systems typically suffer from false negatives, often failing, for instance, to identify people whose heads are tilted. 3-D facial images contain additional information—like nose length—that helps the software make positive matches regardless of viewing angle. Zanen hopes to have his 3-D adapter on the market in the next couple of years.

SEEING THROUGH BLOOD

Even the best medical imaging devices have a hard time seeing through blood. An Israeli startup is out to cure that vision deficiency. Nesher-based CByond has developed a flexible, disposable camera *(right)* that fits on the end of an endoscope or catheter; its image-sensing chip transmits color pictures at ten times the resolution of a 3,000-fiber bundle. CByond has built a prototype five millimeters across and is working on a 1.5-millimeter version. Because blood scatters light, conventional angioscopes can "see" only by temporarily stopping the flow of blood. CByond's camera solves that problem by using polarized light for illumination. A filter passes the polarized light reflected from the artery wall, blocking the unpolarized light scattered from blood cells. The camera should help find areas of the artery wall that are in danger of bursting. CByond plans to begin human tests within 18 months.



COURTESY OF CBYOND (SEEING THROUGH BLOOD); COURTESY OF CARL KING (3-D IN ONE); COURTESY OF SRI INTERNATIONAL (FLATSPEAKERS); JOYCE HESSELBERTH (ILLUSTRATION)

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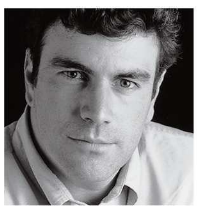
MIMETIC MANAGEMENT

The following examples are not true. But please pay careful attention to them anyway.

- Bill Gates reveals during a CNN interview that the smartest thing he does for his health is get an annual full-body MRI scan. He advises anyone over the age of 40 who can afford to get scanned to do so.
- Warren Buffett tells the *Financial Times* that a new generation of easy-to-use/easy-to-train neural-net software has dramatically improved his ability to pick Berkshire Hathaway Group's stocks. "I can't begin to tell you how important this software is for me," he says. "I'm surprised more hedge fund and mutual-fund managers don't use these things."
- With little fanfare, Tiger Woods begins practicing his swing with a laser-calibrated haptic (force feedback) system that aligns his visor, grip, club head and hips. Both his father and his coach say Tiger credits this technology with boosting his ability to make critical adjustments during competition.



These scenarios are imaginary. But does anyone doubt there would be a tremendous global run on MRI scans, neural-net software and "haptic laser swing trackers" if they were real? Success—even the appearance of success—breeds imitation. With apologies to *Fiddler on the Roof*, let's call it the "Tevye Principle of Innovation Expertise": *"When you're rich they think you really know."* People and institutions are hard-wired to mimic the masters. The imitation heuristic exerts a powerful influence on top management worldwide.

The reality of this "mimetic management" is what so many innovators misunderstand—and it doesn't matter whether they're product, process or service innovators. Imitation may or may not be the sincerest form of flattery—but it is surely the route that innovation most frequently follows into an enterprise. An innovation is not successful until it is widely imitated. Indeed, successful innovators need successful imitators. "Who imitates whom?" defines the diffusion of innovation in the marketplace.

Put another way, the overwhelming majority of organizations manage innovation adoption less by rigorous analysis than by aspirational analogy. They benchmark; they compare; they envy; they emulate. But instead of asking, "What's best?" they ask, "Who's best?" They look at market leaders with an eye toward copying what seems to work. They want what they haven't got.

This means it's not enough for innovators to know what their customers are trying to do; they also need to know *who their customers want to be like.* Do they aspire to be as direct as Dell? Or do they want 3M's bottom-up innovation ethic? Knowing the answer to these questions is vital to understanding how innovations should be packaged or sold so that they enhance their clients' capacity to imitate. Since strategic vision frequently means the ability to spot whose innovating is worth imitating, selling innovation becomes selling the ability to imitate. Innovators must rigorously follow who their customers wish to copy—even if they think those wishes delusional.

Of course, the risks associated with mimetic management are enormous. A questionable "form follows fashion" quality emerges. Once upon a time, emulating Enron's trading infrastructure was a great thing. General Electric, Goldman Sachs and Dell are still seen as enterprises with innovative processes worth emulating. But "best practices" fall in and out of favor. Didn't everyone want to become an e-business? Mimetic managers are particularly vulnerable to the faddishness of faux innovation. Trend is confused with destiny.

However, when Jack Welch's GE made its public commitment to the Internet, when many global giants standardized their operations on enterprise resource-planning software, and when the automobile companies and their tier one suppliers swore they would become "lean manufacturers," then imitating those innovations became imperative.

Organizations manage less by rigorous analysis than by aspirational analogy. They look at market leaders with an eye toward copying what seems to work. They want what they haven't got.

This innovation/imitation cycle perpetuates itself. Consider the auto industry. Once zero-inventory, "lean manufacturing" took root, innovations around "supply chain management," and associated technologies such as scheduling and logistics software, became the standard. Now, as firms in other industries seek to implement their own supply chains, they're looking for leaders to imitate, and any innovators in the supply chain space would be foolish to ignore who their customers (and potential customers) will—or won't—benchmark themselves against. The question those companies are asking isn't "Which vendors have the best supply chain management capabilities?"; it's "Whose do we want our own supply chains to be like?"

Consequently, it's also critical for innovators to know who their customers and clients *don't* want to emulate. It may be that innovation is seen as the best means for differentiating oneself from the competition (as opposed to merely conforming to industry standards). And so who organizations don't want to be like can be even more revealing than who they do.

The result is an intriguing matrix of innovation and imitation: who organizations aspire to be like and who they aspire to avoid, which processes should be innovative and which ones should be imitative. In other words, innovators will have to study the imitation patterns and pathologies of their customers in both innovative and imitative ways.

The obvious big question: who's doing *that* in a world-class manner, so that other innovators can imitate them? TR

INNOVATION

THE FOREFRONT OF EMERGING TECHNOLOGY, R&D AND MARKET TRENDS

RADIO-READY CHIPS

All-silicon radios could make everything wireless

Intel makes microchips, not radios. But if the company's newest manufacturing plans pan out, the distinction between the two products may disappear. According to chief technology officer Patrick Gelsinger, Intel is quickly learning how to build tiny radio transceivers from the same material it uses in microchips: silicon. Research progress inspired Gelsinger to announce in February an audacious plan to put a silicon-based radio on the corner of every microchip the company sells, within as little as five years, at no extra cost to customers.

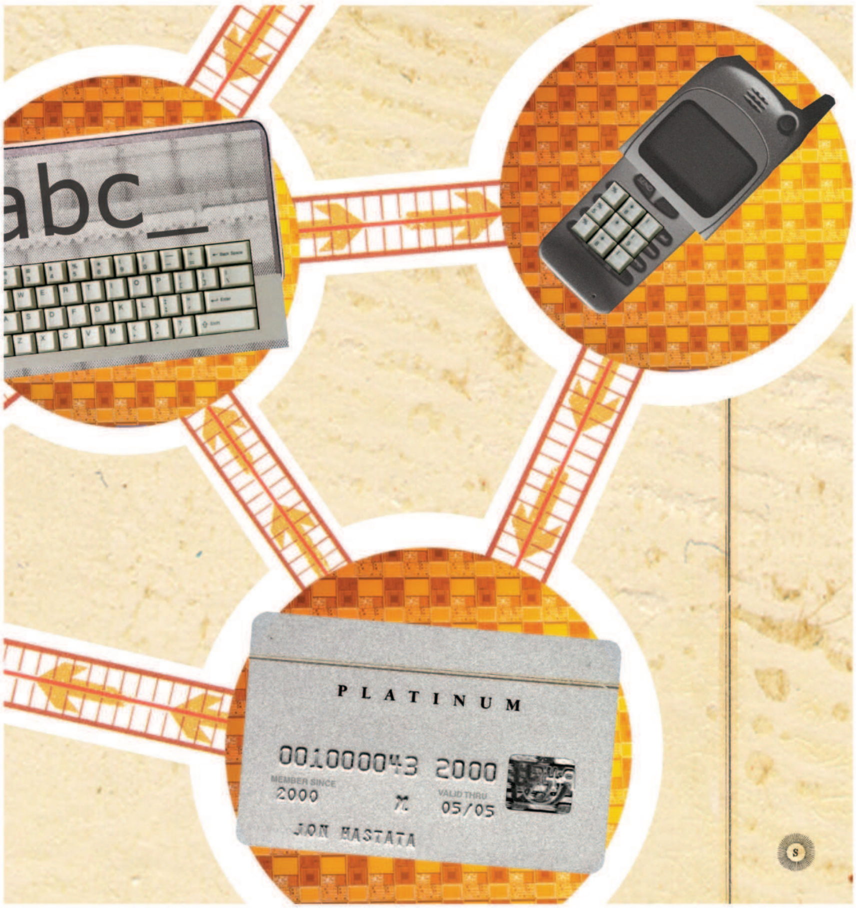
The announcement puts Intel at the forefront of industry efforts to build all-in-one chips that could replace the jumble of costly parts in cell phones and other wireless gadgets. Silicon integrated circuits already dominate when it comes to the digital "back end" of cell phones and other wireless communications devices, where signals are decoded for conversion into sound. But the analog "front-end" components, which capture and amplify radio signals and convert them to digital bits, are typically found on a separate, radio frequency section of the wireless circuit board. This section houses both large, three-dimensional parts such as capacitors and oscillators and transistorized components like amplifiers, which run at such high speeds that they have traditionally been made only using faster, more expensive "compound semiconductors" like gallium arsenide.

But Intel and other chip makers would prefer to stick all these functions onto a single silicon chip, which could be patterned using well-established photolithographic techniques and would cost about one-tenth as much as chips using compound semiconductors. For engineers and computer scientists looking to a future where computing power is ubiquitous and wireless, the potential cost and space savings of putting all of a radio's parts onto the same chip that holds the computing components has a powerful appeal. "We can safely say that any intelligent device needs both a processor and some form of wireless connectivity," says Turner Whitted, manager of the Hardware Devices Research group at Microsoft Research in Redmond, WA. "It makes sense to combine these functions to the greatest extent possible."

There are still big technical barriers to mass-producing silicon radios, such as reducing three-dimensional parts to the micrometer scale with the needed precision and uniformity. But Gelsinger made his announcement on the strength of recent work in the labs of Steve Pawlowski, director of Intel Labs' Communications and Interconnect Technology Group in Portland, OR, and Valluri Rao, who heads the company's Analytical and Microsystems Technologies division. Rao's staff is using silicon to build tiny structures that duplicate the functions of traditional capacitors, oscillators and other components. Pawlowski and his colleagues, meanwhile, are testing silicon circuitry that performs the amplifying, mixing and filtering functions typically handled by separate, more expensive front-end chips. By working out these core technologies, "We're going to be able to dramatically reduce the size and cost of the components required in radio circuits," Gelsinger says.

This is an ambitious agenda, considering that many of these components only work because of their macroscopic size and their three-dimensionality. Oscillators, which help to tune in and amplify radio signals, are one example. These crucial components are often made from quartz crystals that resonate electrically when a voltage is applied, with a resonant frequency partly determined by their dimensions—typically up to a centimeter square. Variable capacitors, used to filter out all frequencies except that of the signal, are another example; they usually consist of interleaved metal plates that hold a varying charge depending on the amount of space between them. Putting space between the plates requires depth, but a typical integrated circuit consists only of thin layers of semiconducting silicon and conducting substrates.

That's why Rao and his fellow researchers have started thinking out of the plane, turning to microelectromechanical (MEMS) manufacturing techniques developed over the last decade in numerous labs at universities and startup firms. These labs have created a wide assortment of tiny structures like beams, bridges and springs from strips of silicon only a micrometer wide. But no one has yet fashioned such structures into a fully functional radio, or built them on a piece of silicon that contains all of the signal-



JASON HOWARD STATTS

Equipped with silicon radios, armies of small, low-power sensors and controllers could eventually infiltrate all our appliances, our structures, and even our bodies.

processing circuitry needed to handle today's digital cell phone transmissions.

Rao and his group believe this can be done without any revolutionary changes in manufacturing techniques. "You can actually build a mechanical device like a variable capacitor using the lithography we have available," he says. Conventional lithography uses light to carve tiny features on silicon chips; MEMS builders go a step further, excavating around these features to make such suspended three-dimensional structures as cantilevers.

Rao's group is using these lithography-based MEMS techniques to build prototype silicon capacitors in which the upper plates are suspended by tiny silicon springs. Applying a voltage makes the plates move up or down, changing the capacitance. It turns out that such structures leak far less charge to surrounding materials than conventional capacitors, Rao says. His researchers are also experimenting with oscillators made from free-hanging cantilevers. "Imagine a tuning fork with one prong, but so small that its resonant frequency is measured in gigahertz," Rao explains. "That lets you start doing things at radio frequencies."

While researchers at Intel and elsewhere have managed to build small clusters of tiny capacitors and resonators, building hundreds or thousands of identical MEMS structures using lithography is still a problem. "We're looking at our lithographic process from the point of view of getting very uniform behavior over a wafer, so that we can build these things at high volume," Rao says.

Pawlowski's group, meanwhile, is demonstrating digital circuitry on silicon for components such as mixers and analog-to-digital converters, achieving what he calls "pretty good signal gain" even at the high frequencies usually handled by gallium arsenide chips. And while they're at it, researchers in his group are designing signal-processing circuitry with the brains to switch between competing wireless-communications protocols. "If somebody is in a Starbucks and they have a connection on their laptop to a wireless local-area network, and they walk out, they need a second radio to keep the connection open," notes Pawlowski. "The promise of this architecture is that it could run multiple protocols without having to have multiple, separate radios."

Laptops, cell phones and other devices that let you roam seamlessly between wireless networks are only one of the industry niches where silicon radios could eventually dominate. Armies of small, low-power, constantly connected devices could eventually infiltrate the appliances and structures all around us. "For example, tiny sensors that communicate through different methods could go inside every window and every ventilation duct to monitor environmental conditions and improve energy efficiency," says computer scientist Gaetano Borriello, who leads an Intel-sponsored ubiquitous-computing laboratory at the University of Washington in Seattle. "Eventually, they could even go inside of people. What we're doing is expanding the range of possibilities."

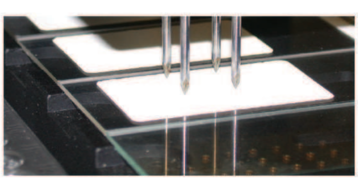
—*Wade Roush*

SWEET SPOTS

BIOTECH | **Doctors commonly diagnose infectious diseases by checking patients' blood for evidence of proteins or genes unique to different bacteria and viruses. Soon, they may be able to look instead for pathogen-specific sugars, thanks to a glass chip developed by biologist Denong Wang at Columbia University's Genome Center. The technology could ultimately be less cumbersome than DNA-based tests and more accurate than protein-based tests for certain pathogens, allowing physicians to quickly screen for thousands of different infectious diseases at once using a small sample of blood.**

When a person is exposed to a bacterium or virus, his or her body produces antibodies that bind to specific sugar molecules on the pathogen's surface. Wang dotted glass chips with some of those same sugars, from bacteria such as Pneumococcus or *Haemophilus influenza*. He then washed blood samples over the chips; if people had been exposed to Pneumococcus, for example, antibodies from their blood stuck to the corresponding sugars on the chips and were then detected through a microscope.

One of the biggest challenges in making sugar chips has been getting the sugars to stick to glass. Wang discovered a relatively simple method: he coated the chip surface with nitrocellulose, which holds the sugars in place. Each of Wang's first chips contains just 48 different sugars, but, he says, "We could spot up to 20,000 different sugars on a single chip, which would allow us to target all the most common pathogens." Wang's goal, in fact, is to create a diagnostic tool that could detect pathogens such as HIV, anthrax and smallpox. He is in discussion with a number of drug companies about commercializing his technology. —*Alexandra Stikeman*



A Columbia University instrument spots sugars onto a chip to make a microbe detection device.

DIGITAL PIRATES BEWARE

Fingerprinting firms crack down on illicit file-sharing

SOFTWARE | So you just downloaded an MP3 version of the latest Jennifer Lopez single from Gnutella or one of the other free file-sharing networks. You're not feeling too guilty, and in any case, no one will ever know, right?

Don't count on it. Lopez's recording label, Epic Records, is owned by Sony Music Entertainment, and Sony is one of a number of media giants hiring the services of a new breed of content-tracking firms to combat digital piracy. These online private eyes are using the latest digital fingerprinting technology to scan public computer networks for unauthorized copies of music files, still images, movies and software. And they can watch as those illicit files spread from hard drive to hard drive—whether or not the files bear the invisible digital "watermarks" often used to identify their original owners.

At San Jose, CA-based BayTSP, for example, software engineers have developed a system that uses the unique characteristics of a client's copyrighted content—amplitude and frequency in an audio file, for example—to extract a digital signature. The system then patrols the entire Internet, including the major file-sharing networks, scanning key sections of five to ten million files per day for matching signatures and automatically e-mailing infringement notices to offenders and their Internet service providers. Because the system doesn't depend on embedded information to find copies, it can be used to locate files that may have been stolen years before the invention of watermarking. "You can give me a piece of pirated content that's been on the Internet for five years, and I can still tell you what it is and where it's being distributed on the Internet," says Mark Ishiwara, BayTSP's chief executive and technology officer.

BayTSP has competitors in the digital-policing market: Arlington, VA-based Cyveillance uses technology similar to BayTSP's to track pirated corporate logos and sensitive business documents, while Seattle-based Loudeye Technologies and Alexandria, VA-based Relatable use the technology to help music companies gauge how widely their songs are being traded. But BayTSP clients such as Adobe Systems, the San Jose-based maker of graphic-arts and document-sharing software, say the company's help in sniffing out and confronting pirates is quickly becoming indispensable. "It gives us an idea of how much pirated product is out there and who's using it," says Cynthia Navarro, manager of Adobe's antipiracy programs.

Still feeling secure about downloading that latest single? —*Wade Roush*

COURTESY OF DENONG WANG (SWEET SPOTS); JAMES YANG (ILLUSTRATION)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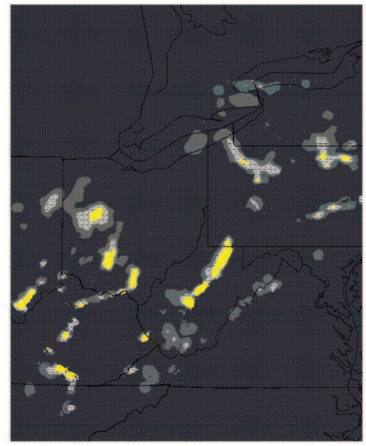
WEATHERING THE FLIGHT

TRANSPORTATION | All too often, bad weather forces planes to make detours of hundreds of kilometers, sometimes creating delays that ripple nationwide. Help is on the way: this summer a new weather prediction system will come on line, allowing more precise air traffic routing, and even showing aircraft safe routes through storms—with a $45 million-per-year projected savings for airlines and travelers.

Designed at MIT's Lincoln Laboratory, the weather prediction system starts with an existing radar network, which covers large regions and updates information every six minutes. Air traffic controllers currently rely on this network to monitor weather in the areas between airports. The new system will incorporate both it and the two additional kinds of radar network that are currently used only to cover air space near airports, but which are more precise and send updates every four seconds. "Nobody had tried to stitch them together before" to cover air space between airports, says Jim Evans, an electrical engineer at Lincoln Labs and lead designer of the system. The technology adds information from satellites, which detect evolving storm clouds that aren't visible on radar, and provides a three-dimensional analysis showing where planes can fly above trouble spots.

The Federal Aviation Administration plans to implement the weather prediction system in the congested Boston-Chicago corridor this summer, where it will provide detailed two-hour storm front predictions that show "holes" in bad weather through which planes can safely fly. "Basically, it will improve efficiency," says Dan Strawbridge, an FAA team leader for weather programs, who is helping implement the Lincoln Lab project. Weather accounts for about 70 percent of aviation delays and costs airlines $3.5 billion annually, he says. "We can do away with some of those delays with this technology," says Strawbridge.



Bright spots indicate storms predicted two hours ahead by a Lincoln Labs radar system.

Indeed, Lincoln Lab said last year that a more localized version of the technology, which it installed in the New York City area, saves travelers and airlines more than $150 million annually *(see "The Digital Sky,"* TR *March 2001).* The new regional system will only work in heavily trafficked corridors that have a high concentration of airports and their radar. But as any traveler to Boston's Logan or Chicago's O'Hare Airports can testify, that's where the delays are happening—at least for now. —*David Talbot*

SOFTWARE AT YOUR SERVICE

LOGISTICS | **Every day, businesses with large service fleets brace for the unpredictable. How many calls for service will stream in during the day? Where will the nearest technicians be, and will they have the right parts in their repair kits? For companies handling hundreds, even thousands, of calls a day, coordinating service is immensely complex—and wrong answers can be immensely costly.**

Now, researchers at IBM are unveiling software that will answer all those questions automatically. The IBM algorithms continually account for data—ranging from which customers have called for service to whether a technician's van has broken down—and periodically churn out instructions representing the best way to deploy the work force at that moment. "I think our approach of continually reoptimizing every 10 to 15 minutes is basically unique to us," says Baruch Schieber, a computer scientist at IBM Research in Yorktown Heights, NY. What's more, he adds, the IBM system relies less on previous calculations when performing new optimizations than other approaches do, so errors don't snowball over time.

Features like this make the IBM tools innovative—and give them unprecedented breadth and power, says David B. Shmoys, a computer scientist at Cornell University. "They're leveraging state-of-the-art theoretical ideas and bringing them to bear on practical problems in an interesting way," Shmoys says. Plus, the IBM approach juggles seven factors, from customer locations to parts availability—a feat that Schieber says is unique in a field where five and six are considered difficult.

IBM started using earlier versions of its algorithms in its own 6,000-employee service unit in 1998 but landed its first customer this year. An IBM commercial product is a sign that the market for service optimization software is booming, says Moshe BenBassat, chairman and CEO of one firm in that business, Campbell, CA-based ClickSoftware. Many companies have already optimized manufacturing, but optimizing service delivery "is a much harder problem" because of unpredictability, he says.

IBM's software aims to tackle such hard problems, so that the unpredictable doesn't have to be unmanageable. —***David Talbot***

JAMES YANG (ILLUSTRATION); COURTESY OF LINCOLN LABS (WEATHERING)

WIRELESS GOES WIDE

An old radio technology learns some new tricks

TELECOM | Wireless data transfer may be the hottest trend in networking, but its newest tool is a 30-plus-year-old technology called ultrawideband.

Although the military has been developing the radio technology—which spreads signals out over a large swath of the radio spectrum rather than sending them at a single frequency—since its invention in the 1960s, the Federal Communications Commission only approved it for limited commercial use in February.

Ultrawideband promises low-power, high-speed data transfer—without the interference problems that plague existing wireless devices, since each transmission is sent in timed, subnanosecond bursts, and receivers ignore all but the in-sync signals. The same physics also gives ultrawideband properties useful for applications like "seeing" through walls and tracking objects in environments with too many obstacles for other radio technologies. A number of companies are gearing up plans for consumer applications.

"A lot of the systems that we have built for the government have immediate commercial interest as well," says Robert Fontana, president of Multispectral Solutions, a Germantown, MD-based ultrawideband company. One example: a wireless intercom built for navy aircraft could be retooled to deliver in-home audio and video. Multispectral Solutions and its competitors plan to manufacture circuits that will enable devices like TVs and speakers to communicate using ultrawideband; each of the companies says it has development partnerships with unnamed consumer electronics companies.

Analysts agree that home networking will initially be the biggest market for ultrawideband. The systems will transfer audio and video from camcorders to televisions and PCs, or from a set-top box in one room to a TV in another; or they'll transfer audio from a stereo or DVD player to remote speakers. In order to comply with FCC regulations, initial systems will be limited to about a 10-meter range. Ultrawideband systems should offer both reduced interference and higher-bandwidth transmissions than technologies like Bluetooth. The first consumer products incorporating ultrawideband should hit store shelves in late 2003.

Consumer applications may quickly move beyond data transfer. "The interesting thing about this technology is that it can be used for different things that you may not necessarily group in one basket," says Mike Wolf, an analyst at Cahners In-Stat Group. Multispectral Solutions and other companies plan eventually to take advantage of ultrawideband's noncommunications capabilities for security systems and location tracking. Eventually, ultrawideband may be able to accomplish what no other wireless technology has, becoming a dominant force in a whole range of applications.—*Erika Jonietz*

OTHER ULTRAWIDEBAND COMPANIES

COMPANY	APPLICATIONS
XtremeSpectrum (Vienna, VA)	Home networking; data transfer
Time Domain (Huntsville, AL)	Home networking; public safety
Pulse-Link (San Diego, CA)	Home networking; location tracking; cellular communications
Æther Wire and Location (Nicasio, CA)	Location tracking (GPS supplement)

MIND MAGNETS

MEDICINE | Alvaro Pascual-Leone holds a figure-eight-shaped paddle to his head and flips a switch. His left arm begins to twitch. He turns off the device—quelling its pulsing magnetic field, which was inducing an electrical current inside his brain—and his arm relaxes. But Pascual-Leone, a neuroscientist at Boston's Beth Israel Deaconess Medical Center, is interested in more than muscle twitches; he believes that magnetic stimulation provides the last, best hope for treating patients with severe depression. This fall, researchers will begin large-scale human trials of the technology to see if he is right.

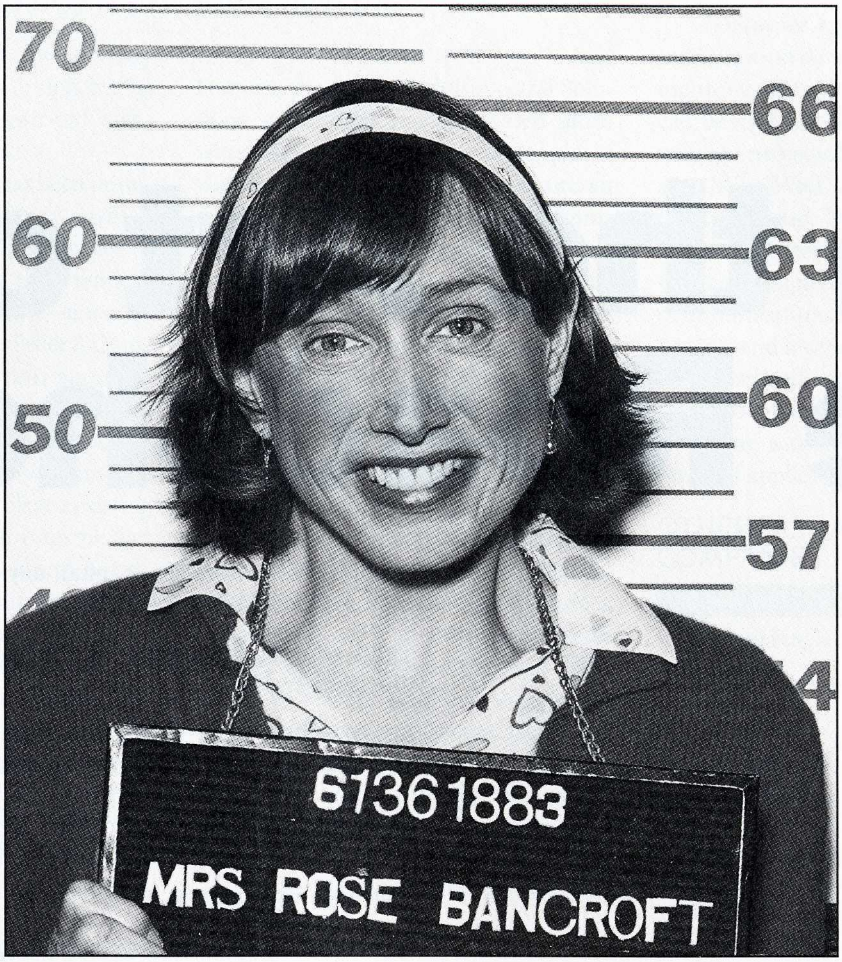
Some 20 million Americans suffer from severe depression, and many of them don't respond to conventional drugs. Based on several small studies, including Pascual-Leone's, regulators in Israel, Europe and Canada gave magnetic stimulation the green light last year as an alternative depression treatment. With a version of the technology licensed from Emory University, Atlanta-based Neuronetics plans to begin human trials, involving 240 patients at eight sites around the country, in September. If all goes well, Neuronetics' CEO Stan Miller hopes to see U.S. psychiatrists offering magnetic treatments for severe depression by 2004.

Neuroscientist Alvaro Pascual-Leone holds a magnetic stimulator.

Mark George, a neuroscientist at the Medical University of South Carolina participating in the trials, sees magnetic stimulation as an alternative to shock therapy. "While shock therapy is very effective, it has lots of side effects such as memory loss, and you have to give the patient a seizure," says George. Magnetic stimulation has none of those side effects. The technique excites nerve cells in a small area of the brain that is underactive in depressed patients.

Still, some believe that the move to the clinic may be premature. "I think the therapy has gotten way ahead of the science," says National Institutes of Health neuroscientist Eric Wasserman. But the reality, say other researchers, is that many depressed patients are desperate for alternative treatments and would gladly try magnetic stimulation despite uncertainties. —*Alexandra Stikeman*

BRIAN WILDER (MIND MAGNETS)



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LEAKY CYBER BORDERS

By the time you read this, I should be filthy rich.

I recently received an e-mail that claimed to be from a high-ranking Nigerian official who had discovered some funds stolen by Nigeria's former military government. The bank account holding this money, I read, could be used only to transfer the funds abroad. All I needed to do was respond with the name of my bank, my bank account number and some personal information. In return, "Dr. Ahmed" would wire me 35 percent of the trapped $41 million.

Of course, this junk e-mail was nothing more than an invitation to be swindled. With my bank information, the good doctor could clean out my savings, wiring the money through a series of other accounts so that I would never see it again.

Like me, you probably delete dubious electronic missives like this one without much thought. But apparently, not everyone is so skeptical. Last year, the Nigerian banking swindle made number three on the National Consumers League's top-10 list of Internet scams. The Federal Trade Commission says that Americans are losing more than $100 million a year to international con artists. But things could be much worse: most of the Nigerian scam letters sent through paper mail get stopped and destroyed at the border by the U.S. Postal Service—ironically, because they are sent with counterfeit stamps.

But while the government vigilantly patrols our physical borders, it is doing precious little to control our electronic ones. Consider this: someone trying to bring fresh fruit from Europe into the United States will be stopped by an agent of the U.S. Department of Agriculture. But there's nothing to protect you from the electronic damage wrought by an infected Microsoft Word file sent to you by some computer hacker in Iraq. Many scholars and civil libertarians say that this is as it should be: while controls on physical borders involve the movement of mere people and things, electronic-border control would regulate information and ideas. Any attempt to block the importation of ideas would be, by definition, an exercise of state censorship. And that, many believe, is a no-no.

But an increasing number of the messages that our computers receive each day from overseas do not carry any ideas at all. These e-mailed files contain sequences of data designed to make our computers crash, or worse, to break into our systems so that foreigners can steal secrets and use our computers as bases for attacking still more machines.

Because of this electronic onslaught, I have followed the lead of many businesses and installed a firewall that relies on "military-strength" cryptography. I have electronic locks, alarms and even an automated intrusion detection system. I will defend myself, no matter whether the attack is from the college freshman next door or a hostile government halfway around the world. Organizations that don't implement these kinds of defenses are considered both negligent and stupid.

As a computer programmer, I have enjoyed the challenge of this constant attention to security. (I have profited from it too, through the books I've written on the subject.) But I'm an unusual case. For most businesses, spending on electronic security is like protection money paid to the mob—necessary for survival but not particularly productive.

This thirst for supersafe electronic security is without parallel in the physical world. We don't berate a fabric boutique for not defending its perimeter with the same vigor and prowess as an aircraft carrier floating off enemy shores. That's because the aircraft carrier (and the rest of the U.S. military) *is* the boutique's first line of defense. The boutique relies on the government for much of its border control, and as a result, the security afforded by the store's plate glass window and five-pin locks is usually more than sufficient.

And that's probably where the world is headed. Just as nations now regulate their physical frontiers, so too will they regulate their electronic ones—using computer security rather than objectionable ideas as their justification. Already, China and many Middle Eastern countries have installed "national firewalls," blocking access to some U.S. Web sites because of their content. France and Germany may soon do the same, blocking access to neo-Nazi content.

The government won't let you bring fresh fruit from Europe into the country. But there's nothing to protect you from the damage wrought by an infected Microsoft Word file sent by some hacker in Iraq.

At a computer conference I attended last summer, one speaker held up a sign that showed a block of Internet addresses that were assigned to Asia. The numbers were surrounded by one of those red circle-and-slash marks. The speaker had gotten so tired of the constant probes, attacks and junk e-mail from those addresses that he had simply cut off their access to his computers. "Asia: just say 'no,'" he said. If this mood spreads, Internet service providers might begin to offer geography-based blocking as a value-added service. Or perhaps there will soon be mandatory firewalls against packets that originate in particular countries. After all, why shouldn't those e-mails from overseas be virus-scanned?

A big part of the Internet's magic is the liberation from concern over distance and borders. Last September's terrorist attacks were so devastating, in part, because a group of attackers from halfway around the world reached through our national borders and attacked civilian targets. The same basic thing—not costing lives, but destroying property and wreaking great economic damage—happens every day on the Internet. TR


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By Clayton M. Christensen

The Rules of Innovation

INNOVATION IS WIDELY CONSIDERED **A BLACK ART— BUT IS IT?** A LEADING BUSINESS THINKER LAYS OUT FOUR ESSENTIAL RULES DESIGNED TO **MAXIMIZE THE CHANCES DISRUPTIVE TECHNOLOGIES** WILL SUCCEED.

Illustrations by Brian Cronin

Two decades ago, when I was just out of graduate school and working in the automotive industry, I got my first introduction to the statistical process-control chart. We used this laborious technique to make sure the machines employed in our manufacturing process did not drift out of control. Composed of three parallel horizontal lines, the "SPC" chart has long been an important tool in quality management. The center line represents the targeted value for the critical performance parameter of a product being manufactured. The lines above and below it represent the acceptable upper and lower control limits. If the product were, say, an axle, workers would plot the thickness of each piece they made on the chart. When I asked why there was typically a scatter of points around the target, my managers cited the randomness inherent in all processes.

The "Quality Movement" of the 1980s and '90s subsequently taught us that there *isn't* randomness in processes. Every deviation of the actual value from the target has a cause. It appears to be random when we don't know the cause. The Quality Movement developed methods for identifying those additional factors—and we discovered that if we could control or account for all of them, the result would be perfectly predictable, and there would be no need to inspect products as they emerged from manufacturing.

The management of innovation today is where the Quality Movement was 20 years ago, in that many believe the outcomes of innovation efforts are unpredictable. The raison d'être of the venture capital industry is belief in the unpredictability of new businesses. A few ventures will succeed; most won't, the VCs say. They therefore place a portfolio of bets, extracting premium prices for their capital in order to earn the high return required to compensate for the risk that unpredictability imposes. I believe, however, that innovation *isn't* random. Every undesired outcome has a cause. Those outcomes *appear* to be random when we don't understand all the factors that affect successful innovation. If we could understand and manage these variables, innovation wouldn't be nearly as risky as it appears.

The good news is that recent years have seen considerable progress in identifying important variables that affect the probability of success in innovation. I've classified these variables into four sets: (1) taking root in disruption, (2) the necessary scope to succeed, (3) leveraging the right capabilities and (4) disrupting competitors, not customers.

Of course, building successful businesses is such a complicated process, involving subtle interdependencies among so many variables in dynamic systems, that we're unlikely ever to make it perfectly predictable. But the more we can master these variables, the more we will be able to create new companies, products, processes and services that achieve what we hope to achieve.

MANY INNOVATIONS FAIL **BECAUSE MANAGERS DO NOT** KNOW WHAT THEY DO NOT KNOW.

Take Root in Disruption

The startling conclusion suggested by the research that led to my writing *The Innovator's Dilemma* was that many successful companies stumble from prominence not because they're badly managed but precisely because they are *well managed.* They listen to and satisfy the needs of their best customers, and they focus investments at the largest and most profitable tiers of their markets. Mastering these paradigms of good management gives established companies, as a group, an extraordinary track record in producing *sustaining* innovations that bring better products to established markets. It matters little whether the innovation is incrementally simple or radically difficult, as long as it enables good companies to make better products that they can sell for higher margins to their best customers in attractively sized markets. The companies that had led their industries in prior technologies led their industries in adopting new sustaining technologies in literally *100 percent* of the cases we studied.

In contrast, the leading companies almost always were toppled when *disruptive* technologies emerged—products or services that weren't as good as those already used in established markets. Disruptive innovations don't initially perform well enough to be sold or used successfully in mainstream markets. But they have other attributes—most often simplicity, convenience and low cost—that appeal to a new, small and initially unattractive (to established firms) set of customers, who use them in new or low-end applications.

The chances a new company could become successful if its entry path was a *sustaining* strategy—trying to make a better product than the incumbents and selling it to the same customers—were about six percent in our study. The chances of success for firms that entered with a disruptive strategy were 33 percent. The disparity stems from the motivation and position of the leading firms. They have far more resources to throw at opportunities than entrants do. When newcomers attack customers and markets attractive to the leaders, the leaders overwhelm them.

All companies are burdened with "asymmetric" motivations in that they must move toward markets that promise higher profit margins and the most substantial and immediate growth and cannot move down market toward smaller opportunities and profit margins. When new entrants take root with customers in markets that are unattractive to the leaders, they are safer—and it has nothing to do with how much cash or proprietary technology they have. They are safe because the incumbents are motivated to ignore or even exit the very markets that the entrants are motivated to enter. Taking root in disruption, therefore, is the first condition that innovators need to meet to improve the probability of successfully creating a new growth business. If they cannot or do not do this, their odds of success are much smaller.

There are two tests to assess whether a market can be disrupted. At least one of these criteria must be met in order for an upstart to be disruptively successful. If a new growth business can meet both, the odds are even better.

1. Does the innovation enable less-skilled or less-wealthy customers to do for themselves things that only the wealthy or skilled intermediaries could previously do?

When an innovation fulfills this condition, even if it can't do all the things existing offerings can, potential customers excluded from the market tend to be delighted. For example, many people loved the first personal computers, no matter how clunky the booting process and limited the software the machines could run, because the alternative to which they compared the PC wasn't the minicomputer—it was no computer at all. Filling such a void reduces the capital commitments and technological achievements required for an innovation to become viable and creates new growth markets. I call the process of finding and nurturing these opportunities *creative creation.* After a technology takes root in new markets, and after new growth is created, disruption can invade the established market and destroy its leading firms.

Even if innovators succeed in cramming disruptive technology into an existing market application, the incumbents typically win. Digital photography, online consumer banking and hybrid-electric vehicles are examples of potentially disruptive technologies that were deployed in such a sustaining fashion. Billions were spent on these innovations to beat out already acceptable and habitual technology; little net growth resulted,

as sales of the new products cannibalized sales of the old; and the industry leaders maintained their rule.

2. Does the innovation target customers at the low end of a market who don't need all the functionality of current products? And does the business model enable the disruptive innovator to earn attractive returns at discount prices unattractive to the incumbents?

Wal-Mart, Dell Computer and Nucor are examples of disruptive companies that attacked the low ends of their markets with business models that allowed them to make money at discount prices. Wal-Mart started by selling brand-name products at prices 20 percent below department store prices and still earned attractive returns because it turned inventory over much more frequently. Such a disruptive strategy can create new growth businesses but does not create new markets or classes of consumers. It has a high probability of success because the reported profit margins of established companies typically improve if they get out of low-end, low-margin products and add in their stead high-margin products positioned in more-demanding market segments. By assaulting the low end of the market and then moving up, a new company attacks, tier by tier, the markets from which established competitors are motivated to exit.

IF WE CAN **MANAGE THE VARIABLES**, INNOVATION WON'T BE NEARLY AS RISKY AS IT APPEARS.

Pick the Scope Needed to Succeed

The second set of variables that affects the probability that a new business venture will succeed relates to its degree of "integration." Highly integrated companies make and sell their own proprietary components and products across a wide range of product lines or businesses. Nonintegrated companies outsource as much as possible to suppliers and partners and use modular, open systems and components. Which style is likely to be successful is determined by the conditions under which companies must compete as disruption occurs.

In markets where product functionality is not yet good enough, companies must compete by making better products. This typically means making products whose architecture is interdependent and proprietary, because competitive pressure compels engineers to fit the pieces of their systems together in ever more efficient ways in order to wring the best performance possible out of the available technology. Standardization of interfaces (meaning fewer degrees of design freedom) forces them to back away from the frontier of what is technologically possible—which spells competitive trouble when functionality is inadequate. This helps explain why IBM, General Motors, Apple Computer, RCA, Xerox and AT&T, as the most integrated firms during the not-good-enough era of their industries' histories, became dominant competitors. Intel and Microsoft (raps about the latter's supposed lack of innovation aside) have also dominated their pieces of the computer industry—compared to less integrated companies such as WordPerfect (now owned by Corel)—because their products have employed the sorts of proprietary, interdependent architectures that are necessary when pushing the frontier of what is possible. This also helps us understand why NTT DoCoMo, with its integrated strategy, has been so much more successful in providing mobile access to the Internet than nonintegrated American and European competitors who have sought to interface with each other through negotiated standards.

When the functionality of products has overshot what mainstream customers can use, however, companies must compete through improvements in speed to market, simplicity and convenience, and the ability to customize products to the needs of customers in ever smaller market niches. Here, competitive forces drive the design of *modular* products, in which the interfaces among components and subsystems are clearly specified. Ultimately, these coalesce as industry standards. Modular architectures help companies respond to individual customer needs and introduce new products faster by upgrading individual subsystems without having to redesign everything. Under these conditions (and only under these conditions), outsourcing titans like Dell and Cisco Systems can prosper—because modular architectures help them be fast, flexible and responsive.

Leverage the Right Capabilities

Innovations fail when managers attempt to implement them within organizations that are incapable of succeeding. Managers can determine the innovation limits of their organizations quite precisely by asking three questions: (1) *Do I have the resources to succeed?* (2) *Will my organization's processes facilitate success in this new effort?* (3) *Will my organization's values allow employees to prioritize this innovation, given their other responsibilities?*

Beyond technology, the resources that drive innovative success are managers and money. Corporate executives often tap managers who have strong records of success in the mainstream to manage the creation of new growth businesses. Such choices can be the kiss of death, however, because the challenges confronting managers in a disruptive enterprise—and the skills required to overcome them—are different from those that prevail in the core business. Many innovations fail because managers do not know what they do not know as they make and implement their plans. That is, they assume that the same strategies and customer needs that apply in mature, stable markets will apply in disruptive ventures. But this is not the case, and by making such assumptions, managers close themselves off from opportunities to discover what customers really find useful in new, disruptive products.

Innovators must avoid two common misconceptions in managing the other key resource, money. The first is that deep corporate pockets are an advantage when growing new businesses. They are not. Too much cash allows those running a new venture to follow a flawed strategy for too long. Having barely enough money forces the venture's managers to adapt to the desires of actual customers, rather than those of the corporate treasury, when looking for ways to get money—and forces them to uncover a viable strategy more quickly.

The second misconception is that patience is a virtue—that innovation entails large losses for sustained periods prior to reaping the huge upside that comes from disruptive technologies. Innovators should *be patient about the new venture's size but impatient for profits.* The mandate to be profitable forces the venture to zero in on a valid strategy. But when new ventures are forced

to get big fast, they end up placing huge bets at a time when the right strategy simply cannot be known. In particular, they tend to target large, obvious, existing markets—and this condemns them to failure. Most of today's envisioned business opportunities for wireless Internet access, for example, involve big applications such as stock-trading and multiplayer gaming that have already found homes on wired, desktop computers. Billions are being sunk into new wireless ventures committed to taking over these markets before innovators have a chance to learn what applications wireless is really best at delivering.

Resources such as technology, cash and technical talent tend to be flexible, in that they can be used for a wide array of purposes. Processes, however—the central element in our second question—are typically inflexible. Their purpose is not to adapt quickly but to get the same job done reliably, again and again. The fact that a process facilitates certain tasks means that it will not work well for very different tasks. Failure is frequently rooted in the forced use of habitual but inappropriate processes for doing market research, strategic planning and budgeting.

Sony, for example, was history's most successful disruptor. Between 1950 and 1980 it introduced 12 bona fide disruptive technologies that created exciting new markets and ultimately dethroned industry leaders—everything from radios and televisions to VCRs and the Walkman. Between 1980 and 1997, however, the company did not introduce a single disruptive innovation. Sony continued to produce sustaining innovations in its product businesses, of course. But even the new businesses that it created with its PlayStation and Vaio notebook computer were great but late entries into already established markets.

What drove Sony's shift from a disruptive to a sustaining innovation strategy? Prior to 1980, all new product launch decisions were made by cofounder Akio Morita and a trusted team of associates. They never did market research, believing that if markets did not exist they could not be analyzed. Their process for assessing new opportunities relied on personal intuition. In the 1980s Morita withdrew from active management in order to be more involved in Japanese politics. The company consequently began hiring marketing and product-planning professionals who brought with them data-intensive, analytical processes of doing market research. Those processes were very good at uncovering unmet customer needs in existing product markets. But making the intuitive bets required to launch disruptive businesses became impossible.

A company's values—the focus of question three—determine the necessity of spinning out separate organizations for new ventures. Values are even less flexible than resources. *Everyone* in an organization—executives to sales force—must put a premium on the type of business that helps the company make money given its existing cost structure. If a new venture doesn't target order sizes, price points and margins that are more attractive than other opportunities on the organization's plate, it won't get priority resources; it will languish and ultimately fail.

Nor is it just the values of the innovating company that matter, because suppliers and distributors have values too, and *they* must put the highest priorities on opportunities that help *them* make money. This is why, with almost no exceptions, disruptive innovations take root in free-standing value networks—with new sales forces, distributors and retailing channels.

Disrupt Competitors, Not Customers

The fourth factor in successful innovation is minimizing the need for customers to reorder their lives. If an innovation helps customers do things they are already trying to do more simply and conveniently, it has a higher probability of success. If it makes it easier for customers to do something they weren't trying to do anyway, it will fail. Put differently, innovators should try to disrupt their competitors, never their customers.

IF AN INNOVATION HELPS CUSTOMERS DO THINGS MORE SIMPLY, **SUCCESS IS MORE LIKELY**.

The best way to understand what customers are actually trying to do, as opposed to what they say they want to do, is to *watch* them. For example, when interviewed by the college textbook industry, students say they would welcome the ability to probe more deeply into topics of interest that textbooks just touch on. In response, publishers have invested substantial sums to make richer information available on CDs and Web sites. But few students actually use these innovations, and little growth has resulted. Why? Because what most students *really* are trying to do is avoid reading textbooks at all. They say they would like to delve more deeply into their subjects. But what they really *do* is put off reading until the last possible minute—and then cram.

To make it simpler and more convenient for students to do what they already are trying to do, a publisher could create an online facility called Cramming.com. Like all disruptive technologies, it would take root in a low-end market: the least conscientious students. Semester after semester, Cramming.com would then improve as a new "cramming-aid" growth business, without affecting textbook sales. Conscientious students would continue to purchase textbooks. At some point, however, learning the material online would be so much easier and less expensive that, tier by tier, students would stop buying texts. This path of innovation has a much higher chance of success than a direct assault that pits digital texts against conventional textbooks.

The observed probabilities of success in innovation are low. But these statistics stem from the sum of sustaining and disruptive strategies, many of which are attempted in organizations whose resources, processes and values render them incapable of succeeding. Many innovators draw lessons from observing other successful companies in very different circumstances and attempt to succeed with just one or a few links in a chain of interdependent values. And many fail after assuming that what customers *say* they want to do is what they actually *would* do.

Hence, the observed probabilities of success don't necessarily reflect what the true likelihood of success can be, if the critical variables in the complex and dynamic process of innovation are understood and managed effectively. Indeed, success may not be as difficult to achieve as it has seemed. TR

Harvard Business School professor Clayton M. Christensen, a former Rhodes scholar and successful entrepreneur, specializes in the management of technological innovation.

CLONING CAN'T BE STOPPED

Human clones are fodder for horror films and heated debate. Time after time, though, our procreative urges have outweighed our fears and moral qualms about baby-making technologies.

essay by daniel j. kevles
illustrations by jo tyler

DOLLY, THE WORLD'S MOST FAMOUS SHEEP, WAS CLONED FROM THE UDDER CELLS OF AN ADULT EWE.

On announcing her birth in 1997, embryologists Ian Wilmut and Keith Campbell, who had engineered her, noted that she had been named in honor of the entertainer Dolly Parton. Wilmut explained, "No one could think of a more impressive set of mammary glands than Dolly Parton's." Parton responded, "I'm honored."

Dolly's birth was a milestone in the engineering of animals for food and medicine, but not everyone was as pleased as Parton by the event, much less by the implication that the same methods might be used to clone human beings. On the contrary: since Dolly's arrival, the prospect of human reproductive cloning has been widely condemned by clerics and ethicists, politicians, pundits and scientists as unethical, unsafe and socially dangerous.

Yet human cloning will almost surely happen. In the past, other new reproductive technologies were also denounced at first; but then they were adapted to serve human procreational needs and ultimately became commonplace practices. Human cloning already has advocates—according to polls, six to seven percent of adult Americans, including, no doubt, many who cannot or prefer not to have children by conventional means. If human cloning is made reliably safe for both mother and child, market demand for it will gain considerable force, likely overpowering the residue of moral objection.

At the moment, the moralists enjoy a strong advantage. Ian Wilmut himself opposes human cloning, calling it "offensive." Clerics of many different faiths attack it as a violation of God's order; ethicists denounce it as a denial of the cloned child's right to a unique genetic identity. Social critics warn that cloning would simply permit the rich to indulge in reproductive egomania or entrepreneurs to mass-produce superior athletes. In a recent report, a panel appointed by the National Academy of Sciences concluded, based on animal experiments conducted since 1997, that production of babies by cloning "is dangerous and likely to fail" and that human reproductive cloning should be legally prohibited. Laws banning it have been enacted in 24 countries, including France, Germany, the United Kingdom, India, Japan, South Africa and Brazil. Calls for the prohibition of human cloning have been strongly endorsed by President George W. Bush and the U.S. House of Representatives, though not—as *Technology Review* goes to press—by the Senate.

The outcry brings to mind the great biologist J. B. S. Haldane's *Daedalus*, a slim book of reproductive utopianism published in 1924. Haldane held that the Daedalus of Greek mythology was the first biological inventor (the first genetic engineer, we would say) because he was connected with the creation of the Minotaur through the coupling of Pasiphaë and the Cretan bull. Daedalus escaped punishment from the gods for his hubris, Haldane noted, but he suffered "the age-long reprobation of a humanity to whom biological inventions are abhorrent."

While Daedalus did not offend the gods of his day, many people have indicted innovators in reproductive technology for affronting God, or ethics, in ours. Haldane's ideas were mocked in Aldous Huxley's *Brave New World*. In the 1930s, artificial insemination was promoted as a means to a radical eugenics by, among others, the American biologist Hermann J. Muller, a socialist and future Nobel laureate. At the time, eugenics had yet to be discredited by its association with the Nazis, and Muller, along with other biologists on the left, thought that a eugenic revolution could be achieved if outstanding men could spread their seed via artificial insemination. To Muller's mind, so "many women...would be eager and proud to bear and rear a child of Lenin or of Darwin...that restraint, rather than compulsion, would be called for." Muller was naive to think that women would eagerly make themselves into vessels for the sperm of great men, but his ideas were also thwarted by the moral conventions of the day, which held artificial insemination—even to compensate for a husband's sterility—to be tantamount to adultery.

In the early 1970s, the British scientists Patrick Steptoe and Robert Edwards faced moral condemnation for their research into the creation of human embryos through in vitro fertilization. The medical ethicist Leon Kass, claiming that infertility was a social problem rather than a medical one, contended that such fertilization was not therapeutic because it did not cure women of that condition. Kass—now the head of President Bush's bioethics commission—insisted that by making embryos in the lab, biologists like Edwards were doing experiments on "potential human subjects" who might suffer birth defects because of the procedure but who could not give their consent. Paul Ramsey, a theologian at Princeton University, found implications of eugenics—now a dirty idea following the revelations of the Nazi death camps—in test-tube fertilization. He insisted that it was a manufacturing process that, if coupled to genetic engineering, might enable parents to choose "to have a girl rather than a boy, blond hair rather than brown, a genius rather than a lout." He wanted such fertilization prohibited on moral grounds, and so did the American Medical Association.

Haldane knew that although a given biological innovation might initially be seen as a perversion, over time it could become accepted as "a ritual supported by unquestioned beliefs and prejudices." Acceptance depends on social circumstances and the purposes to which the innovation is adapted. The women's movement that began in the 1960s, by emphasizing a woman's right to control her own body, led a few women to avail themselves of the Repository for Germinal Choice, the so-called Nobel Prize sperm bank, a venture in Escondido, CA, that Muller's ideas had inspired. But the women's movement helped infinitely more to divorce artificial insemination from both its eugenics connection and its adulterous connotation and associate it with the simple desire to have a child.

In England, Edwards—confident in his results from in vitro fertilization with lower animals—effectively rebutted the warnings of critics like Kass with the July 25, 1978, birth of Louise Brown, the world's first test-tube baby, perfectly formed and healthy, a joy to her hitherto infertile mother. By the mid-1990s, more than 150,000 babies fertilized in petri dishes had been born, and with in vitro fertilization clinics proliferating around the world, the number today could be higher than 500,000. Follow-up studies of test-tube babies have concluded that, while twice as many come into the world with handicaps such as low birth weight, nine out of ten of them are no more likely to suffer from disease or disability than conventionally conceived children.

Surrogate motherhood, in which one

woman carries a fetus for another, was also condemned at first as immoral and exploitative but has since become commonplace. Thanks to advances in prenatal diagnosis, many women at risk for bearing children with genetic or chromosomal disorders resort to abortion if their fetuses have lost the roll of the genetic dice. It seems inevitable that human cloning, if made medically safe, will undergo similar taming and adaptation to human wants.

According to polls, a majority of the U.S. public already supports so-called therapeutic human cloning—the creation of cloned embryos for research, particularly on stem cells—and so does the National Academy of Sciences. President Bush and his conservative allies, including Kass, object to research cloning, saying it creates life only to destroy it, but they appear to be fighting a rear-guard moral action. The mere prospect that human therapeutic cloning will pay medical dividends has so far sufficed to block the absolutists in the Senate who want to ban human cloning for any purpose. If work with embryonic stem cells begins to yield actual treatment for disease, therapeutic cloning will become even more common in the lab than artificial insemination and in vitro fertilization are in the clinic.

Therapeutic cloning today will hasten the arrival of reproductive cloning tomorrow. Even without it, cloning techniques and technology are advancing rapidly. Since Dolly, cattle and pigs have been cloned, and so have mice, goats, cats and rabbits, with techniques that are said to be promising for overcoming the practical difficulties in getting human clones to grow. Human cloning research will surely yield still further improvements in safety and reliability—and someday, somewhere, lead a biologist to implant a cloned embryo in a willing woman's womb.

The demand for human reproductive cloning is already evident. Calls for permitting it have come from gay men, lesbians and infertile couples who wish to have genetically related children, and from people who want to clone lost children or other relatives. James Grifo, a fertility specialist at New York University Medical Center, has said of cloning opponents, "None of them have seen the misery my patients are living through." Still, human clones will not be what some people expect—replacement duplicates of their sources. They will, like everyone else, be born as babies. Each will be genetically the same as its clonal parent, a new kind of identical twin; but since each will be shaped by environmental influences different from those the parent encountered, each will develop uniquely.

If human cloning is made reliably safe for both mother and child, market demand for it will gain considerable force.

Yet human clonal reproduction will open uncharted territory in familial dynamics, especially where children are raised by their clonal parents. No twin has ever been called into being and then reared by its identical sibling. How the child will turn out psychologically and emotionally is anybody's guess. But that uncertainty will not stop prospective clonal parents, just as similar unknowns about how children will turn out have of course not stopped conventional reproduction.

Once reproductive cloning is made physically safe for the fetus, its enthusiasts may find an ally in U.S. law. The U.S. Congress, of course, could decide to ban human cloning for any purpose, claiming the power to do so because it can regulate interstate commerce, and a cloning clinic would be open to women from anywhere in the country. But such a law could well run afoul of the U.S. Supreme Court's ruling in *Roe v. Wade*, which, by upholding the right of a woman to choose an abortion, arguably implies that the state cannot interfere with how she chooses to reproduce.

The first human clone will probably be born outside the United States—perhaps in China, where work on human cloning is reported to be proceeding. Wherever the child appears, its birth will undoubtedly electrify the world. Unlike Louise Brown, this baby will not fade immediately into the noise of daily life; people will want to know with much greater interest if it is healthy, and if it remains so. If it does, one imagines that other cloned children will follow and become commonplace—beneficiaries, like Louise Brown's successors, of a new commodity in the growing emporium of human reproduction. TR

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As the founder of Microsoft Research, Nathan Myhrvold helped shape the course of computing. Now he's eyeing tomorrow's transforming technology—and working on an economic theory of everything.

PHOTOGRAPH BY TIMOTHY ARCHIBALD

Q & A

myhrvold's exponential economy

Nathan Myhrvold looms as one of today's great polymaths. Master's degrees in geophysics and space physics at age 19, doctorate in mathematical and theoretical physics and an apprenticeship under Stephen Hawking, presidency of a software company—and all this before becoming Microsoft's chief technology officer. He spearheaded the founding of Microsoft Research, one of the world's most influential computer science labs, and played a leading role in a number of the company's development projects, including some that contributed to Windows NT and Windows CE. Along the way he found time to train as a gourmet chef and learn to drive race cars. More recently, Myhrvold's been digging for dinosaurs and mastering photography: his office is adorned with photos from trips to Hawaiian volcanoes, Alaskan tundra and the California desert.

But for Myhrvold, now 42 and with a fortune of several hundred million dollars, it is only a beginning. In January 2000, even before formally leaving Bill Gates's fold, he cofounded Intellectual Ventures with former Microsoft chief software architect Edward Jung. Not exactly a venture capital firm because it's funded by the founders, mainly to pursue their own ideas, the

company is exploring everything from new forms of computing to biotech and genomics. Myhrvold is also thinking about launching the Invention Factory, an effort to unite leading inventors and change the way inventing is done *(see "The Invention Factory,"* TR *May 2002). TR* editor at large Robert Buderi visited Myhrvold in Bellevue, WA, to learn about his vision of a world in the midst of an unprecedented explosion of technological growth.

TR: I've seen Intellectual Ventures described as a biotech company, an incubator, a venture capital firm. What are you doing?
NM: The reason I decided to leave Microsoft is, I wanted to do whatever I wanted to do. So our mission here is about as eclectic as I am. One of the areas I've been very interested in is biotech, and no matter how broad a scope I can carve out for our research group at Microsoft, biotech was just a little too far out. So I've met lots of people, I've gotten smart on a bunch of areas, I've invested in some companies, I've talked about forming other companies, and that's the stage I'm in.

I've [also] gotten very interested in the economics of technological revolutions, and how is it that we've had such enormous growth in technology over the past 30 years or so. I've spent a lot of time comparing the differences between the technological revolutions of the current century and latter part of the 20th century to the revolutions in, say, the 19th century. What I've found is it wasn't just the technology that caused enormous economic change, because in the 19th century, between Edison and a whole host of other inventions and tremendous industrial growth, there were huge, huge changes. I believe there is something more fundamentally different. And it's fundamentally different because of the emergence of exponentially growing technologies, where the next step is as big as all the previous steps put together, and you are dealing with changes that happen by factors of millions or billions. In the tech industry, we talk about Moore's Law and the drastic changes in the price/performance ratio of processing power every 18 months or so. However, I've found that exponential growth can happen in other industries when certain criteria are in place. So I've been trying to put some order to this notion, since no aspect of classical economics really captures this idea.

TR: Can you explain this further? I would have thought that if you're looking at electric power or telephony it would have exhibited exponential growth for a time.
NM: If you look at the number of homes connected to electricity, or the number of homes connected to a telephone, yes, you could say that the growth was exponential. [But] if you look at it from the perspective of the price/performance ratio, the cost of electrical power per kilowatt-hour or the cost of a minute of phone service, those costs really didn't decline very much.

The cost of shipping was dramatically affected by the railroad, but we've hunted up all the records on what was the cost of shipping a ton of grain, all throughout the 19th century. It improved by about a factor of ten. The price of steel improved by maybe a factor of three. All of those things went through a price/performance ratio change. But typically less than a factor of 10. Whereas from the first transistor to today, the improvement was something like a factor of a billion.

There are dozens of areas undergoing a similar kind of exponential growth. The technological revolution for the 21st century is going to be based on which areas those kinds of exponential growth rates catch hold in, and which ones don't. That is the key issue for the 21st century in technology.

TR: Besides semiconductors, what other technology areas have you identified as undergoing exponential growth?
NM: If you look at hard disks, the number of bits you get for a buck on a hard disk grows at about 125 percent per year. Mass-market software has an exponential price/performance curve. If you bought Microsoft Windows or Adobe PageMaker or—pick any other application you could possibly imagine—and you look at it over a period of time, you're paying almost the same amount or even less in real dollars for an increasing amount of technology—an exponentially increasing amount.

The tools of molecular biology are on that kind of a path. Genomics is going through an exponential revolution. So regardless of whether you're a doctor trying to save somebody's life, or you're trying to make new cosmetics, genomics and proteomics and the tools associated with them become indispensable. The Human Genome Project was a gigantic project, eight years, $12 billion, to sequence the entire human genome. And I claim it'll be down to the $10 range to sequence individual genomes.

TR: To sequence your own genome?
NM: Not just your own genome, but every economically important plant and animal needs to be sequenced. Everything that eats us, all these disease organisms and parasites need to be sequenced so that we can develop cures and better protect ourselves. We're on the cusp of so many interesting advances in so many parts of science and industry, but based largely on the fact that you have these incredible technologies that continue to be cheaper and cheaper and cheaper and cheaper.

TR: What areas will Intellectual Ventures—or the Invention Factory—be targeting?
NM: I'm very open minded as to what topics we're going to look at. I have a background in computing. And I was once a physicist. So those areas are near and dear to my heart. Biology is interesting because you have a variety of breakthroughs, conceptual and instrumentation breakthroughs, that have made biology a symbolic, information-rich science.

TR: What is a symbolic science?
NM: Something with deep abstractions described by lots of data. Vast amounts of data—and analyzing abstract data is one of the most important frontiers in biology and medicine. So understanding which of your genes have this, that and the other thing, or which things are being expressed in your body right now. What proteins are in over- or undersupply. Where is there a feedback control system that's screwed up. We're on the verge of figuring out that or a million other very complicated systems. A key tool in that's computing. So bioinformatics, bioinformatics algorithms. Most of that stuff is at its complete infancy. One thing that's amusing to me is that when I visited proteomics companies, you get people, although they use computers, they use them in completely boneheaded ways. So everybody has big SQL databases, big Oracle databases, under the faith that that's a good thing to do, when it's completely ill suited. The relational database was designed for tasks such as tracking stock room inventory or managing employee information; it was not designed for manipulating genomic base pairs and genetic information. So some-

body needs to invent a bunch of stuff there. But more than that, biology and medicine are about reverse-engineering a very complicated machine. The detailed understanding of all the mechanisms and pathways by which things are regulated and controlled, the ways in which disease disrupts those regulations and how we can put them right, that's all incredibly complicated. Well, that suggests all kinds of opportunity. What tools are missing? What are the analysis techniques that you need to do? There are a million things.

TR: We have all this growth in technology, but you have been quite vocal in also pressing for more basic science.

NM: Basic science is the fundamental well from which all this stuff is watered. Ironically, basic science is being given increasingly short shrift. DARPA [the U.S. Defense Advanced Research Projects Agency] funding for computer science is probably the single most successful government program in the history of governments—it led to this entire revolution in computing. Yet most Silicon Valley companies that are the beneficiary of that don't invest in fundamental research. Then you get the ludicrous thing of people in Congress saying they want more relevant research. No, you should have less relevant research.

I've done extensive modeling of all of this. If you're a company that lives hand to mouth, don't do research, okay. You don't need me to tell you that. If you're a company that has steady cash flows, then you should work at whatever level you can afford. So if you're a company that intends to be around 20 years from now, like a Microsoft, you are losing money if you don't do research. It is an incredibly profitable investment only open to a limited club—the people who can afford to take a long-term view. And that's an industrial research context. At the government level, you really should swing for the fences.

You could make a case that research funding really won the Cold War, because it was those economic things that stoked the economy. As soon as the Soviets went from being our enemies to being potentially our friends, [people said,] now let's stop giving lots of money to science. Well, that doesn't make any sense. Fundamental science has been the best investment the government's ever made.

TR: A big mark against basic research in industry is that the firms who support it don't always capture the benefit of it—Bell Labs with the transistor, Xerox with so much of modern computing.

NM: Whether you're expanding overseas or you're doing any business decision, you can find someone who screwed it up and caused lots of hurt to their company. It hasn't stopped people from doing it.

So take Xerox as an example. The same era that they started PARC [the Palo Alto Research Center, birthplace of the graphical user interface, Ethernet and other elements of digital computing], they bought a company called Scientific Data Systems. They lost a billion dollars in 1970 dollars on that. More money than they've spent on PARC the entire time they've had PARC. Nobody gives them any shit for that anymore. Everyone says, oh, Xerox screwed up PARC. They didn't screw up PARC. PARC invented the laser printer. That one invention alone paid for PARC many times over. Yet people give Xerox a black eye for this. Why? Because they think, "But they should have done more." Well, if you do shoulda, woulda, coulda, you're going to drive yourself crazy. The problem that Xerox had—the fundamental problem—is that Xerox didn't understand computers. That's why they lost the billion dollars in that other merger. That's also why they couldn't commercialize any of the other computer inventions.

So you add it up, investing in basic research makes huge sense for companies. But it makes even more sense for the government. By the way, I'd love to have the rest of the world join us, because research is the kind of thing that feeds on other research. The fundamental researcher in China that isn't being funded today might be the one who if he was funded would find the cure to the disease I'll get in 20 years.

> "Basic science is the fundamental well from which all this stuff is watered. Ironically, basic science is being given short shrift."

TR: You mentioned Microsoft as one company doing fundamental research, which you had a role in. What about the rap that Microsoft is not able to innovate?

NM: When I first got into computers, there was no Microsoft. IBM was considered this big company that dominated the industry and wasn't very innovative, yet if you look at their patents or the history of the first things that they did, IBM was the most innovative company in large computers. IBM got a reputation for not being such because the computers they sold generally made sense, and their innovation was packaged in something that was incredibly pragmatic and practical.

Fast-forward 30 years, Microsoft's in the same position. Microsoft tends to package its innovation in things which are incredibly practical. Yet they often are very, very innovative. Sometimes in incremental ways, sometimes in revolutionary ways. Let me take my favorite example of a Microsoft program that was way ahead of its time. Windows. I was development manager when it was 2.0. Everybody now acts like Windows was part of the firmament, destined to be a success. No, it was an incredibly hard battle to convince the industry that the graphical user interface was good. The key ideas were invented at Xerox; Apple and Microsoft both commercialized it. And both Apple and Microsoft deserve a tremendous amount of credit for that.

TR: Let's come back to something you mentioned right off the bat—a theory that accounts for this new period of exponential growth. Can you elaborate?

NM: People want to have the next Silicon Valley. The interesting thing is not so much the next Silicon Valley in a geographic sense, it's what are the next [technological] areas that will undergo this kind of growth two, five, 10 years and 50 years from now? And how does that reshape the world? I think it's possible to go about that in a more deliberate way. To actually say, this is what you should look for. This is how you should do it—and then nurturing them over that hump.

But I'm still working on it. TR

Edifying ruins: The *Vasa*, recovered from the Baltic Sea in 1961 *(this page)*, the collapsed walkways of Kansas City's Hyatt Regency *(top right)* and the burned-out Iroquois Theater *(bottom right)* in Chicago all offer lessons about how technology fails.

10 TECHNOLOGY DISASTERS

As horrific as technological failures can be, they often teach valuable lessons. By Eric Scigliano

Let's face it: something draws us to a disaster, as long as it doesn't strike too close. And in all endeavors, but especially in technology, failures—even ghastly, gruesome, cataclysmic ones—can sometimes make better teachers than spectacular successes. The 10 examples offered below, drawn from a span of 373 years, show that though technologies change, many of the factors that make them go spectacularly wrong are surprisingly consistent: impatient clients who won't hear "no"; shady or lazy designers who cut corners; excess confidence in glamorous new technologies; and, of course, good old-fashioned hubris.

In assembling this list of exemplary technological disasters, we've omitted the most familiar—those whose names have entered into the language, like Bhopal, Chernobyl, Three Mile Island, *Titanic* and *Challenger*—in favor of some with fresher tales to tell and lessons to impart. These events vary widely as to when, where, how and why they happened. But they all show how trusted technologies can suddenly go wrong, and how flaws that seem trivial or, in retrospect, painfully obvious can have devastating consequences.

CORBIS (THEATER); CORBIS (VASA); AP (HYATT)

The *Vasa* sinking

The Swedish flagship *Vasa*'s first and final sailing in August 1628 left fine fodder for future management consultants—an all-purpose cautionary tale of an overbearing but technically clueless boss pushing through his pet project. King Gustavus II Adolphus, striving to make Sweden a superpower, had wanted four new warships built fast. Workmen were already laying the *Vasa*'s keel when the king ordered its length extended. His seasoned master shipwright, fearing to challenge the famously hot-tempered king, went ahead. The shipwright then took ill, directed the project as best he could from his sickbed and died before it was finished. His inexperienced assistant then took over, and the king ordered a second gun deck, possibly spurred by false reports that rival Denmark was building a ship with double gun decks. The result was the most lavishly appointed and heavily armed warship of its day, but one too long and too tall for its beam and ballast—a matchless array of features on an unstable platform. When the standard stability test of the day—30 sailors running from side to side trying to rock the boat—tilted the *Vasa* perilously, the test was canceled and the ship readied for launch. None of Gustavus's officials dared bear the bad news to the absent king, who was by then off warring in Poland and impatiently awaiting his new superweapon. Minutes after her grand launching, with all Stockholm watching, the *Vasa* heeled, listed and sank, killing about 50.

The Hyatt Regency walkway collapse

When three "floating walkways" crashed to the floor of Kansas City, MO's swank new Hyatt Regency on July 17, 1981, speculation first fixed on the patrons who'd been dancing on them: perhaps their high-stepping had set off a harmonic wave that made the sky bridges buckle and crumble.

The truth proved more prosaic. The hotel's engineers had originally designed two of the three walkways to hang on common, vertical metal rods. But the metal fabricator took a fatal shortcut, substituting shorter rods hanging from one level to the next. The second-floor walkway thus hung from the fourth-floor, doubling the weight on its connectors. The fabricator claimed to have requested approval for this change; the engineers insisted they

Derailed system: High-speed rail's first fatal crash occurred in 1998 when a train on the Inter City Express line near Eschede, Germany, clipped an old-style bridge support. The wreck killed 101 people.

weren't asked, though they had signed off on final drawings that included it. The designers had also asked to be on site during construction, when they might have spotted the change, but were rebuffed by an owner determined to avoid additional expense. When enough patrons filled the walkways, the connections gave way. Thanks to miscommunication and corner-cutting, 114 perished in the deadliest structural failure in U.S. history.

The Iroquois Theater blaze

What the *Titanic*'s sinking represented at sea, the burning of Chicago's Iroquois Theater marked on land: a supposedly indestructible, up-to-the-minute design—in this case, a theater advertised as "absolutely fireproof"—destroyed with an enormous loss of life. The Iroquois's owners acted with as much haste and hubris as their *Titanic* counterparts, installing no firefighting equipment, forgoing fire drills and opening before the sprinkler system was ready. Instead, like so many others, they relied on a single technological magic bullet: an asbestos curtain that would drop down and shield the audience in the (rather common) event of a backstage fire. On Dec. 30, 1903, as vaudeville star Eddie Foy regaled the overcapacity crowd in *Mr. Bluebeard*, an oil-painted backdrop brushed against a hot calcium-arc spotlight and ignited. The asbestos curtain started dropping on cue but caught on a stage light. Crew and cast opened the stage door to flee, admitting a powerful gust that sent fireballs shoot-

AP (TRAIN)

ing out over the unshielded audience. Fleeing patrons either found the doors barred or could not turn the newfangled latches on them. Six hundred two died, more than twice the toll of "the Great Chicago Fire" 32 years earlier.

The Eschede train derailment

Sometimes even the safest technology is vulnerable to the not-so-perfect world around it. In the 34 years since the inauguration of high-speed rail, no line anywhere in the world had suffered a fatal accident. All that changed on June 3, 1998, on the Inter City Express line near Eschede in northern Germany, when a small improvement in comfort derailed this carefully managed system. High-speed trains generally run on solid "monobloc" metal wheels, but to dampen noise and vibration the Inter City Express (like many lower-speed light-rail systems) wrapped these in metal "tires" cushioned with rubber inserts. Inspectors examined the tires daily, but even ultrasound failed to detect a minute crack in one tire. It broke, causing a partial derailment. But the train continued upright and likely would have reached a safe stop if it hadn't chanced to pass under an old-style roadway bridge that, unlike newer bridges, rested on a central pillar, which stood between the line's two tracks. A swinging car clipped the pillar, and the bridge collapsed on the train, causing a massive pileup and 101 deaths. So it goes, all too often, when new, high-performance technology is inserted into older infrastructure built to operate with a greater margin of error. The high-speed train was a round peg in the square hole of an outdated rail corridor.

The Ashtabula Creek Bridge wreck

The United States' deadliest bridge collapse demonstrates the dangers in transposing what works in one material to a new, unproven one. In 1863, Cleveland railroad magnate Amasa B. Stone Jr. announced a bold advance in bridge technology—so bold it was never imitated. For two decades, the state of the art in American bridge design had been the reliable Howe wooden truss system, which added threaded iron upright supports to a classic structure of diagonal wooden trusses. The iron connectors provided more strength and eliminated the painstaking joinery of all-wood truss construction. So, Stone reasoned, why not go all the way and re-create the Howe design entirely in iron? Trusting too much in this newer, costlier material, Stone ignored both its potential for hidden weak spots and an essential flaw in his design: the bridge was assembled like an interlocking jigsaw, held together by pressure rather than the firm attachments of the wood originals; if one joint went, the whole structure would. Nevertheless, Stone proclaimed his 1865 creation "absolutely sound," and it stood for 11 years, even as its parts shifted. Then, on Dec. 29, 1876, as a passenger train crossed, an iron support with a hidden air bubble collapsed, the bridge tumbled down, fires spread from the train's tipped-over woodstoves, and more than 100 riders perished.

The St. Francis Dam burst

It's never wise to underestimate the forces of nature. William Mulholland, creator of the Los Angeles water system and a designer of the Hoover Dam and Panama Canal, met his Waterloo at the little-remembered St. Francis Dam in San Francisquito Canyon, 72 kilometers northwest of L.A. On March 12, 1928, one day after Mulholland examined it and declared it sound, the dam burst, sending a wall of water, reported as 24 meters high, hurtling toward the Pacific. More than 500 people in its path perished. An inquest blamed unstable rock formations for the collapse, but later investigation suggests that the dam's base was thinner than believed, and its engineers did not fully understand uplift forces or build in seepage relief. The underlying failure was more universal: the United States saw a boom in dam building in the first decades of the 20th century, as engineers threw up walls against the waters in unfamiliar terrain and on a scale never before attempted. They did so in large part by guesswork and extrapolation from much smaller projects. Ambition outpaced knowledge, and inevitably some of the new dams failed—most catastrophically the St. Francis. But its collapse left an important legacy: the world's first dam safety agency, uniform engineering testing criteria and a state-mandated process for arbitrating wrongful-death suits still used today. Too late for Mulholland: "I envy the dead," he intoned at the inquest, and faded into seclusion.

The *Atlantic Empress/Aegean Captain* collision

If ever there was an accident waiting to happen, it was your typical oil supertanker. These floating monsters can stretch over 400 meters, weigh more than 400,000 metric tons and require five kilometers to stop. And yet they are astonishingly undermanned, underpowered and ill prepared for unexpected problems. Where many smaller ships use multiple propellers to steer and brake, most tankers have just a single massive propeller. And the tools that help compensate for these limitations can contribute to a false sense of security; two ships relying on radar, which is great for navigating unchanging environments, may wind up traveling too fast to break from a collision course. Industry critics warned of an eventual collision between two supertankers, and on July 19, 1979, it happened: the *Atlantic Empress* and the *Aegean Captain* (which was apparently hauling bootleg oil to apartheid South Africa) collided near Tobago in an unexceptional rainstorm. Together they lost 26 crewmembers and spilled more than 185 million liters of oil—more than four and a half times as much as the *Exxon Valdez* spilled in 1989. But because it happened out of sight, this, the largest tanker spill ever, was soon out of mind and off the news.

The day AT&T's lines went dead

The Y2K bug was the long-awaited disaster that didn't happen; the AT&T crash 10 years earlier was the software disaster everyone thought couldn't happen. Ma Bell had one of the world's largest and most famously reliable networks: hurricanes and earthquakes couldn't shake it, a 1989 U.S. Congressional report on the general unreliability of government software lauded the dependability of AT&T's, and the company's ads impugned the glitches that pestered upstart competitors Sprint and MCI. Then, on Jan. 15, 1990, a single switch at one of AT&T's 114 switching centers suffered a minor mechanical malfunction, momentarily shutting down that center. When it came back up, it sent out a signal that made other centers trip and

Fatal combination: An Air France Concorde burst into flames moments after takeoff in July 2000. The cause: low-tech design flaws and some bad luck.

reset—and send out similar signals. The centers crashed, writes Leonard Lee in *The Day the Phones Stopped,* "like a hundred mud wrestlers crowded into a too-small arena," each pulling himself up by pulling down the others. American Airlines estimated it lost 200,000 reservation calls, and CBS couldn't even reach its local bureaus to check on the story. The culprit proved to be a single line of faulty code in a complex software upgrade recently implemented to speed up calling. AT&T's much touted backup switching system carried the same fault and suffered the same crash. "The condition spread," AT&T chairman Robert Allen confessed afterward, "because of our own redundancy." The company did not keep that redundancy sufficiently insulated from the main system; it could have retained the old software in its backup system until it had thoroughly road-tested the new. But just maybe, the company's programmers had come to believe their own good press.

The 1965 Northeast blackout

California's rolling blackouts in 2001 sent pundits harking back to the great 1965 Northeast blackout. But reckless deregulation, market manipulation and artificial shortages did not figure there as in California. Instead, the causes were technical—and stemmed from efforts to *prevent* shortages and blackouts. When electricity usage soared in the 1950s, power companies sought to ensure supplies by joining New York, New England and Ontario in a vast grid. When demand spiked in one locale, others would fill it. But in a twist that illustrates just how difficult it can be to predict how vast, complex networks will actually work, the engineers didn't anticipate the effects surging *supply* in one area might have on others—effects that brought the whole grid down. The trigger was a single relay switch on a line bearing power from Niagara to Ontario, which had been set to trip off if power surged past a certain level. On Nov. 9, 1965, the power load exceeded that level, the switch tripped off—and the power that would have flowed to Toronto surged back into western New York, swamping the lines and causing generators to shut off to avoid getting fried. The cycle spread, south to New York City and east to the Maine border. Thirty million people across 207,200 square kilometers were cast into darkness. New Yorkers, who afterward claimed the regionwide blackout as their own, muddled through peaceably—dining out by candlelight, sleeping by the thousands in hotel lobbies, helping strangers. But one famed outcome—a baby boom nine months later—proved to be just legend.

The Concorde crash

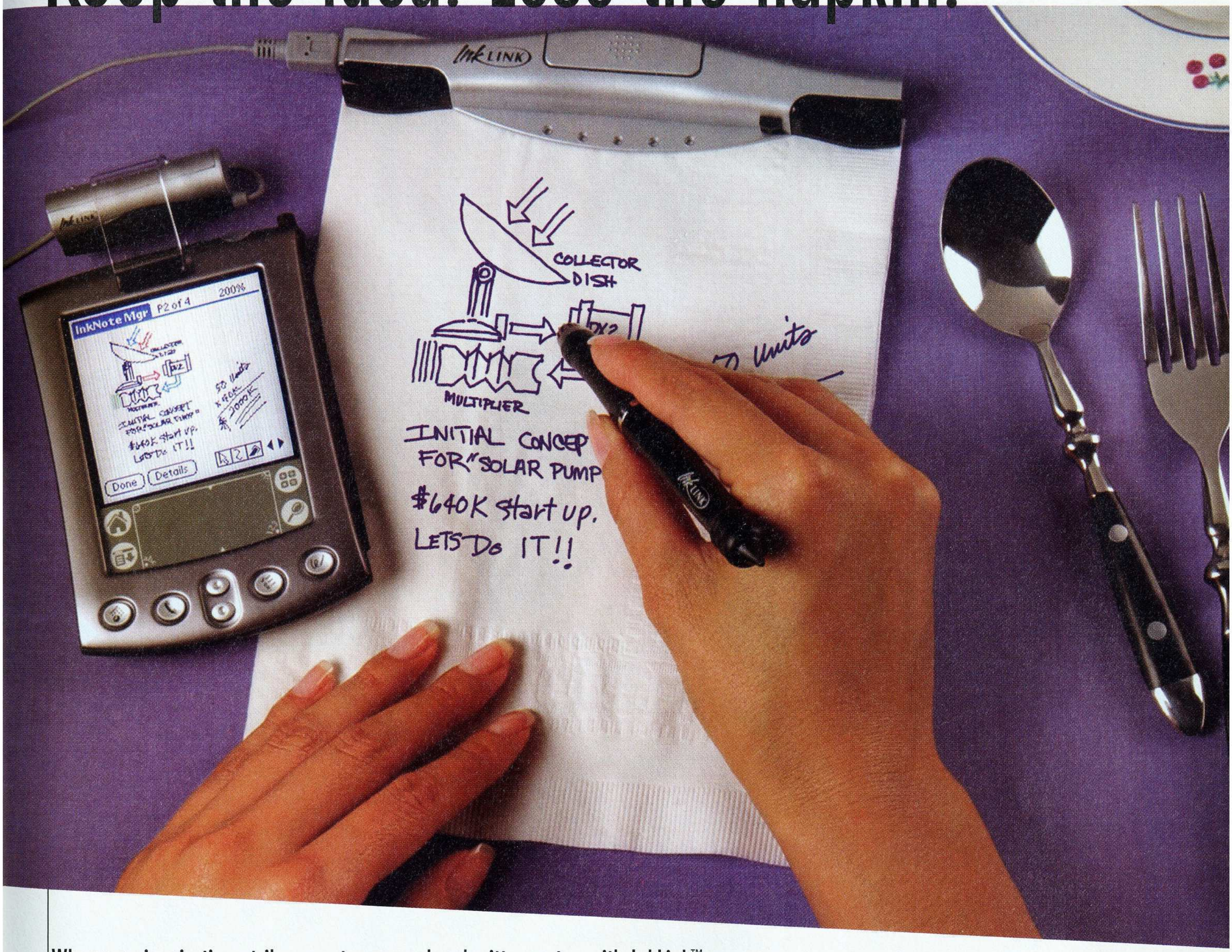
Until July 25, 2000, the supersonic Concorde was aviation's star in safety as well as speed. Before its first flight, its engineers tested it longer—for 5,000 hours—than any other plane in history; in 26 years and tens of millions of kilometers of transatlantic flights, the Concorde fleet had suffered not a single fatality. But for all its superb structural, aerodynamic and propulsion design, the Concorde bore a fatal combination of lower-tech flaws—proving the adage that it's the little things that'll get you. Its high takeoff speeds wore hard on its tires, which would often blow out despite being changed five times as often as those on an ordinary jet. And the fuel tanks in its wings were not strongly reinforced against impact, a precaution standard in newer planes.

It took just one more little mishap to make a disaster: a titanium "wear strip" fell off a Continental DC-10 in the path of an Air France Concorde leaving Paris. When the Concorde's tire hit the strip, a chunk of rubber tore off and smashed into the wing, punching a 600-square-centimeter hole in its skin and causing fuel to leak and ignite. The resulting crash killed all 109 people aboard the flight, as well as four on the ground. Air France and British Airways subsequently installed new tires tested to repel titanium strips at speeds up to 403 kilometers an hour, as well as undercarriage reinforcements and bulletproof tank liners to prevent similar fuel leaks. One arguably foreseeable accident source had, belatedly, been eliminated. TR

To join an online discussion of this article, visit www.technologyreview.com/forums/disasters

AP (CONCORDE)

Keep the idea. Lose the napkin.



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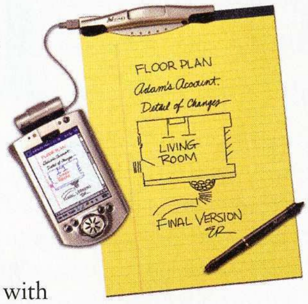

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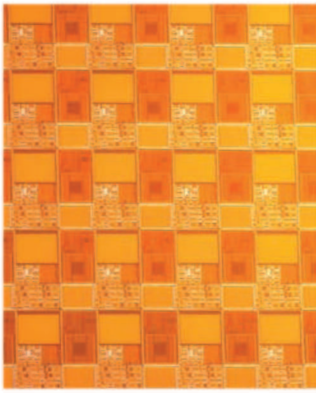
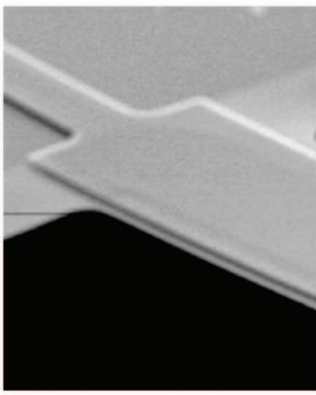
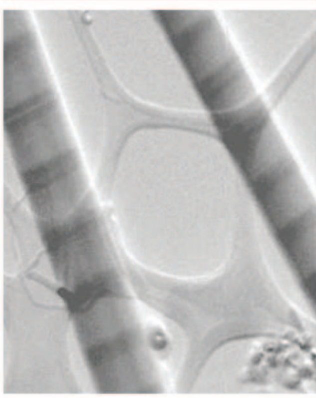
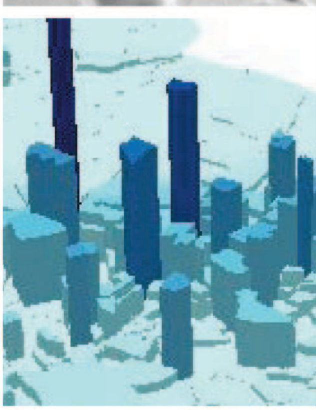








THE STATE OF INNOVATION

In the two-plus years since the first TR100, the "state of innovation" has undergone a radical transformation. Long gone is the dot-com phenomenon—whatever that was—as is the irrational exuberance over telecom and e-commerce. Biologists have completed a draft of the human genome, offering a starting point for an entirely new way of practicing medicine. Nanotechnology has progressed faster than even its most rash advocates imagined, promising everything from ultrafast computers to cheap and quick diagnostics. And information technology continues to permeate almost everything we do—be it through biometric safeguards for "homeland security," tiny sensors for monitoring roadways, or the networked home.

In the following pages, *Technology Review* identifies and explains today's dominant trends in information technology, biomedicine, transportation and nanotechnology. Needless to say, prognosticating the future of technology is a risky business. But we dared to, after talking to dozens of experts in each field and many of this year's TR100 members (whose names appear in **bold**)—today's leaders and tomorrow's stars. The result is a snapshot of the technologies that will transform industries or create new ones in the next five to ten years. This is the state of innovation in 2002.

INFORMATION TECHNOLOGY

COMPUTING POWER IS GROWING BY DISAPPEARING—FREEING US TO THINK ABOUT BUSINESS, NOT BITS. BY WADE ROUSH

It's no news flash to say that computers are going to keep getting smaller, as they have for the past 50 years. But even as they vanish from sight, computers will, in an important sense, grow much larger.

That's because the time is coming when computing devices connected in a wireless web will permeate our entire physical environment, toiling behind the scenes to monitor and manage our houses, factories, roads, vehicles—even our bodies. But this lofty vision will be realized only through a series of small improvements in computing's nuts and bolts. Some researchers, for example, are developing ways to bring new capabilities to the existing Internet, such as powerful network-based services that can link a company's inventory systems with its accounting and customer databases. Others are studying technologies to broaden the Web's physical reach—among them more power-efficient microchips and high-quality broadband wireless systems.

In the world created by these converging trends, networked computing devices will surround us—but we will no longer think of them as "computers." They'll simply be part of the furniture. We're already well down that road. "Your car has dozens of processors that adjust all kinds of things, yet you just think of them as the heating system and the air bags and the brakes," says Richard Burton, who manages distributed-systems research at the Palo Alto Research Center in the heart of Silicon Valley. "You're not aware of all the computation there."

This movement—toward what's variously known as "ubiquitous," "pervasive" or "embedded" computing—is hardly new. But it is gaining momentum. Thanks to recent advances in underlying technologies such as semiconductor manufacturing and networking software, proponents have moved beyond the stage of spinning gauzy theories and started tackling the technical problems. "Ubiquitous computing will be the dominant paradigm in information technology," predicts TR100 judge Juzar Motiwalla, a partner at Green Dot Capital in Singapore.

At first blush, it might seem that computing is already ubiquitous. After all, the World Wide Web transformed the Internet from the province of academic scientists into history's biggest town library, village marketplace and sidewalk soapbox. Now, though, software designers, including several members of this year's TR100, are turning the Internet and the Web into the media we'll use to stay connected, share our favorite content, tap into distant computing resources and run our businesses—and do it all faster.

Justin Frankel of AOL Time Warner, for instance, is the originator of Gnutella, an ingenious program that lets PC users link directly to each other's hard drives through the Internet. The result is a Napster-style file-sharing free-for-all, without a central database or server that ticked-off copyright owners can shut down. But music sharing is only the beginning of what these "peer-to-peer" programs could do. A computer employing such software uses the Internet to locate a handful of other machines running the same program; these machines are connected to even more machines, and so on, eventually forming vast webs that can propagate search requests and files. Gnutella's power to easily copy and move documents around the network could make it easier to store information wherever disk space is available, for example, as well as to keep one step ahead of potential censors.

At the other end of the computing-power scale from Gnutella, researchers like **Steve Tuecke** of the Argonne National Laboratory in Illinois are writing software that unifies supercomputers around the

world into a single "grid." Tuecke was the lead software architect for Globus, open-source "middleware" that provides a common language for accessing distant supercomputers, data-gathering instruments and scientific databases. Globus includes tools for automatically locating the hardware and software scientists need, authenticating legitimate grid users and parceling out parts of a computational task to whatever facilities have spare processing cycles. While Globus is now used mainly by research scientists, IBM, Microsoft and other companies have adopted it as a step toward new and potentially lucrative network-based services.

Such services use newly standardized Web protocols to give users access to e-business software running on any kind of computer on the Internet, taking over data-intensive tasks like inventory management, scheduling and accounting. In addition to the big firms already exploring this area, "A whole host of new companies will come along to provide Web services," predicts TR100 judge Anthony Sun, a general partner at Venrock Associates, a Menlo Park, CA, venture capital firm.

Case in point: Bang Networks, a San Francisco startup founded by **Tim Tuttle**. Recognizing that the performance of Internet-distributed software might suffer due to network bottlenecks and lost data packets, Bang developed "intelligent routing" that maintains secure communications. "In dollar terms, these business-to-business and business-to-consumer services are going to remain the dominant aspects of ubiquitous computing for the near future," says TR100 judge Philippe Janson, who works in IBM's Zurich Research Laboratory on the kind of computer networking hardware that forms the hidden "back end" enabling such services.

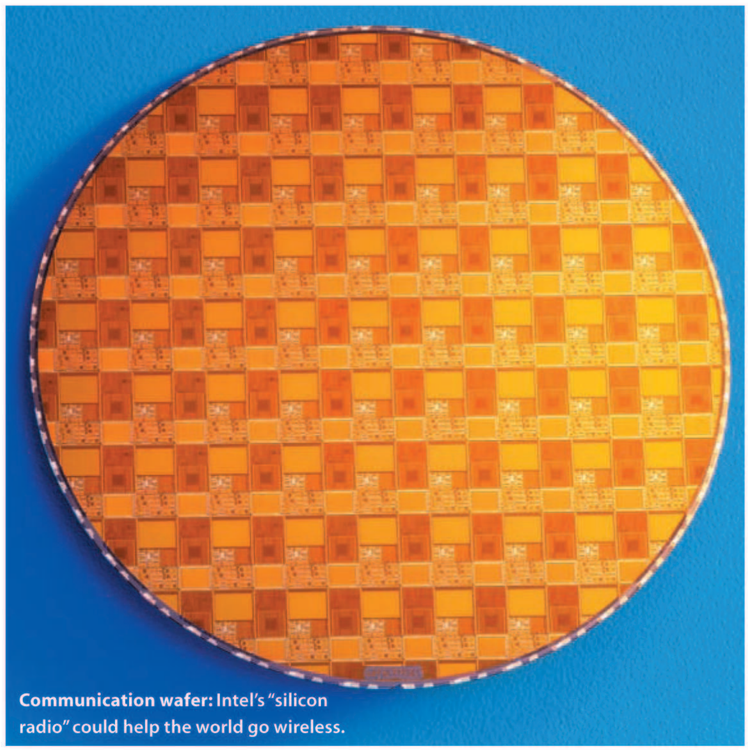
Making the computer networks we have faster and smarter makes good economic sense. But technologies like peer-to-peer file sharing, grid computing and Web services may only reach their full potential when we no longer have to stay riveted to our desktop PCs to use them. "Until anybody can have access to broadband content anytime, anywhere, we are not done with the infrastructure," says Sun.

This challenge hasn't escaped the attention of infotech researchers. MIT's **Vahid Tarokh**, for example, has invented a way to keep wireless signals strong long after they've left a transmitter by broadcasting the same signal from multiple antennas. Such technology, combined with emerging standards for packing more data into radio transmissions, could extend bandwidth-hogging Web services to cell phones and handheld computers.

Chip makers are betting that such technologies will unlock the Internet in a way that businesses and consumers can't resist. This spring, Intel announced plans to build radio transceivers into all of its silicon chips by 2010. This development could reduce the number of components in—and hence the cost of—mobile, connected devices. And Sunnyvale, CA-based National Semiconductor has created an entire division dedicated to building energy-efficient chips for devices like lightweight, tablet-sized Web terminals. The company's latest Geode chips, which feature a control processor that puts components to sleep between bursts of activity, use about one-tenth the power of the microprocessors inside today's PCs. Such chips should fuel the development of portable information appliances—as well as the networked sensors and controllers that will extend our awareness into our surroundings.

These devices promise to help with the chore of running the technological infrastructure and to bring us varieties of information never before available—for example, real-time data on the structural integrity of bridges or buildings during earthquakes or terrorist attacks. But to be practical, such highly distributed systems will need the ability to diagnose and fix their own bugs and to reroute messages around lost nodes. The software to accomplish this remains very much on the drawing board. "We have a lot of work to do on the plumbing," says Gaetano Borriello, head of an Intel-sponsored ubiquitous-computing lab in Seattle.

Which is another way of saying that the TR100 and their information technology peers will have to keep innovating—finding new ways to furnish the future with intelligent machines that draw their power from their very invisibility. TR



Communication wafer: Intel's "silicon radio" could help the world go wireless.

COURTESY OF INTEL

BIOMEDICINE

OVER THE NEXT DECADE, PERSONALLY TAILORED DRUGS AND DIAGNOSTIC TECHNOLOGIES COULD CURE WHAT AILS *YOU*. BY ALEXANDRA STIKEMAN

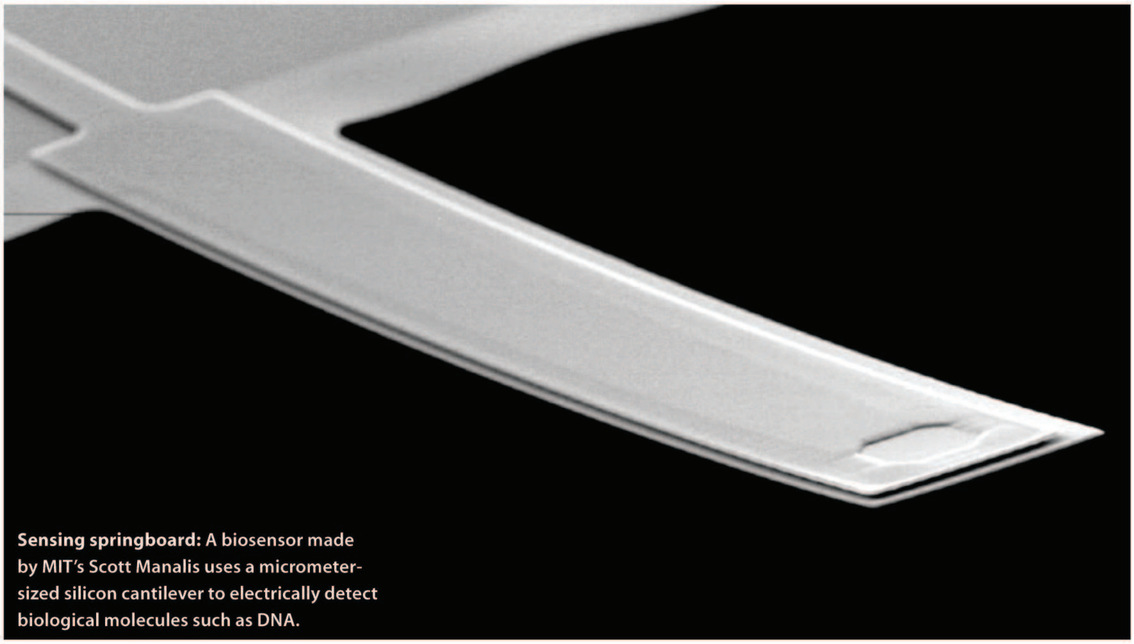
Your dirt-biking expedition has ended painfully—a few ribs broken in a tumble on the trail—and the emergency-room doctor has sent you home with a bottle of codeine. It should be enough to tide you over until the bones heal, unless you're one of the 20 million Americans who have a mutated form of an enzyme called cyp2d6, which normally converts codeine into the morphine that soothes pain. If you are, the enzyme won't work, and the pills won't even take the edge off. Worse yet, neither you nor your physician will know that until you take the drug.

Such is the reality of medicine today. Physicians can prescribe a drug based on a patient's symptoms, but the hidden details of an individual's genetic or molecular makeup can make him or her the wrong patient for that drug. Medications work differently in different people. What's more, in the case of diseases like cancer or arthritis, a patient's symptoms alone don't always tell doctors exactly what's wrong; subtle molecular differences can underlie seemingly similar illnesses. So choosing the treatment most likely to fix the problem is a hit-or-miss proposition. But that one-drug-fits-all reality is beginning to give way to a new era of "personalized medicine," in which physicians can diagnose their patients with unprecedented accuracy and treat each of them with drugs tailored not only to the disease, but also to the patient's genetic or metabolic profile.

"It's going to totally transform medicine, there's no question about it," says Susan Lindquist, director of MIT's Whitehead Institute for Biomedical Research. "And it's going to be happening soon." Mark Levin, CEO of Cambridge, MA-based Millennium Pharmaceuticals, offers one vision of what personalized medicine might mean for a patient: "When we walk into the doctor's office 10 years from now, we'll have our genome on a chip." Using that chip, Levin says, a doctor will be able to determine what diseases a patient is predisposed to and what medicines will provide the most benefit with the fewest side effects. Even the way we think about disease will be different, says Jeffrey Augen, director of life sciences strategy at IBM, because doctors will make diagnoses based on genes and proteins rather than on symptoms or the subjective analysis of tissue samples under a microscope. "So instead of a person having chronic inflammation or cancer, he or she will have a cox-2 enzyme disorder or a specific set of genetic mutations," Augen predicted at a recent conference in Boston.

The change is possible due in large part to emerging technologies that enable researchers to identify and analyze genes and proteins with phenomenal speed—thereby pinpointing the exact nature of different diseases and predicting individuals' responses to drugs. Even using conventional DNA and protein analysis technologies, researchers have already taken some first steps toward personalized medicine. A woman with breast cancer, for example, can take a gene- or protein-based test that reveals whether her cancer will respond to certain drugs. But the key to gathering the massive amounts of genetic and molecular information that will expand personalized medicine's reach—and make it a commonplace tool in the doctor's office—is the thumbnail-sized biochip. These chips can analyze thousands of genes, proteins and other molecules at once from a single drop of blood.

One of the first triumphs for biochips in uncovering the molecular differences between diseases was a study led by biologists Patrick Brown at Stanford



Sensing springboard: A biosensor made by MIT's Scott Manalis uses a micrometer-sized silicon cantilever to electrically detect biological molecules such as DNA.

COURTESY OF SCOTT MANALIS

University and Louis Staudt at the National Cancer Institute in 2000. Using DNA microarrays—glass wafers spotted with thousands of DNA strands—the researchers examined patterns of gene activity underlying a type of cancer called non-Hodgkin's lymphoma. After examining nearly 18,000 genes, they discovered that what was once thought to be one disease was in fact two distinct diseases. What's more, the chemotherapy regimen normally prescribed for non-Hodgkin's lymphoma patients was significantly less successful for patients with one of those two diseases—a clear indication that better knowledge of what's going on at the genetic level could help doctors make better decisions about treatment.

DNA chips might soon begin to inform physicians' decisions about how they prescribe some of the most commonly used pharmaceuticals. Santa Clara, CA-based Affymetrix and Basel, Switzerland-based Roche Diagnostics have teamed up to develop biochips that could help predict patients' responses to such drugs as antidepressants and blood pressure regulators. The devices will be able to screen for several different mutations in the gene for the cyp2d6 enzyme—which helps metabolize a number of drugs in addition to codeine—and in another key enzyme gene. Roche aims to have the chips on the market by early 2003.

Even-more-sophisticated biochips might ultimately provide a quicker means of reading genetic fingerprints right in the doctor's office. One drawback of existing DNA chips, for example, is that researchers first have to modify the sample of DNA in order for the chip to detect it. But physicist **Scott Manalis** and his group at MIT's Media Laboratory are fabricating a silicon microchip that could potentially provide instant notification when it detects specific gene sequences in a sample of blood. In their device, micrometer-sized silicon cantilevers sense the molecular charges associated with biological molecules such as DNA and could produce a telltale electrical signal. "This opens up the possibility of making a simple biosensor for point-of-care diagnostics," says Manalis.

Sometimes, however, DNA doesn't tell the whole story. It's often the proteins encoded by the DNA that actually determine whether a person is sick or well, and whether a drug is beneficial or toxic. Biologist **David Sabatini** at the Whitehead Institute found a way to look at the real-life activity of proteins by building arrays of living cells on glass chips. Sabatini recently cofounded the biotech firm Akceli in Cambridge, MA, to commercialize his technology, which he hopes to start selling to drug companies by mid-2003. Drug researchers could, for instance, equip each cell on the chip with a different variant of the body's drug-metabolizing enzymes, and then expose the chip to a variety of drugs. By monitoring the cells' responses, researchers could determine if a drug is toxic across the board, only to people with a particular enzyme variant, or not at all. "You can essentially create drug side-effect profiles," says Sabatini. If a drug is toxic to some people but otherwise looks promising, a company may decide to pursue its development, targeting it to only those patients it benefits. Such a drug, developed specifically for people with not only a particular disease but a particular metabolic profile as well, would be the epitome of a personalized medication.

In the next decade, more and more such drugs, and the diagnostic tests necessary to choose among them, will begin to hit the market. So in the future, when you go to pop a pill you haven't tried before, you won't have to wonder if it's really the right drug for you. You'll know. TR

NANOTECHNOLOGY

RESEARCHERS COULD DELIVER FAST, CHEAP NANOELECTRONICS SOONER THAN ALMOST ANYONE HAD PREDICTED. BY ALAN LEO

Three years ago, when Rice University chemist James Tour pitched his nanotechnology startup to investors, he had a hard time getting anyone to listen—despite his track record as one of the world's most accomplished experts in nanoscience. Today, Tour says those same investors are all ears. "After working in this area for 13 years and having people say, 'That's pie in the sky. It'll never work,' it's gratifying to see some validation from the investment community," he says.

To call it "some validation" is putting it mildly. The company Tour cofounded in 1999, Molecular Electronics, was one of the first to seek to commercialize scientific breakthroughs in nanoelectronics. But in the last year alone, with advances coming faster than almost anyone had predicted—and with venture capitalists suddenly interested—dozens of nanotech companies have formed, backed by hundreds of millions in investments.

While Molecular Electronics plans to build computer memory using individual molecules to store bits of information, others are taking aim at ultrasensitive biological sensors, or flat-panel displays, or nanoscopic lasers. What these efforts have in common is an ambition to use components mere nanometers (billionths of a meter) in size to replace conventional electronics. "Things have gone crazy in the last year," says Paul Weiss, a chemist at Pennsylvania State University. "We're a lot further than we thought we'd be a year ago."

Nanotechnology will likely affect vast sectors of the economy, from biotechnology and health care to energy. But if scientists like Tour and Weiss are correct, the biggest impact will come from nanoelectronics. For electronics manufacturing, the promise is smaller, faster and cheaper products than conventional approaches could ever achieve. And advances have come with remarkable speed. In 1998, researchers struggled to rig up a single nanoelectronic component: a molecule that acted as a rudimentary switch. Research teams now are connecting dozens of these nanoscale components and are looking to the next step: how to assemble entire devices, such as memory chips.

Today, silicon microchips have features as small as 130 nanometers. But continuing to shrink silicon chips is getting expensive and difficult. "At some point, silicon is going to run out of steam," says John Rogers, director of nanotechnology research at Lucent Technologies' Bell Labs and member of the 1999 TR100. "You're going to need something else." Something, Rogers says, like transistors the size of single molecules. Although still at least a decade from commercialization, chips built using these molecular transistors are the industry's best hope for building faster, cheaper computers well into this century.

"With the electronics we're talking about, we're going to make a computer that doesn't just fit in your wristwatch, not just in a button on your shirt, but in one of the fibers of your shirt," says Philip Kuekes, a computer architect at Hewlett-Packard Laboratories. Kuekes and his colleagues are designing circuits based on perpendicular arrays of tiny wires, connected at each intersection by molecular transistors. By the middle of the decade, Kuekes says, Hewlett-Packard will demonstrate a logic circuit about as powerful as silicon-based circuits circa 1969. "We're trying to reinvent the integrated circuit—with its logic and memory and interconnects—with a consistent molecular manufacturing process," Kuekes says.

Well before the first shirt-thread computer boots up, however, companies will begin to integrate nanoelectronic components, including tiny wires and ultradense computer memory, into

conventional silicon electronics. Hewlett-Packard and Molecular Electronics, for example, both plan to have prototype memory devices ready as early as 2004. Devices that store a bit of data in a single molecule could provide thousands of times more storage density than the electronic memory currently used in computers.

Researchers are also working with nanoelectronics to develop new biological and chemical sensors not possible with conventional technology. University of California, Berkeley, chemist Peidong Yang is one researcher developing such sensors from silicon nanowires. Yang explains that contact with even a single molecule changes the wires' electronic state. Researchers can measure that change to identify unknown molecules for purposes of diagnosis or pathogen detection.

To fully realize the possibilities of nanoelectronics, however, researchers must clear several major hurdles. First, they must build robust nanoelectronic components that function as fully, reliably and efficiently as silicon—no small task, given the semiconductor's 50-year head start. Last fall, Bell Labs' **Hendrik Schön** made significant strides toward that goal by fabricating a molecular transistor that matches its silicon cousins in one key characteristic: gain, or amplification of current as it passes through the transistor. Without this amplification, the electrical signal quickly fades, and multiple devices can't work together as complex logic circuits. "We can not only switch with this device but amplify the current; therefore these transistors are suited to be building blocks of larger circuits," says Schön.

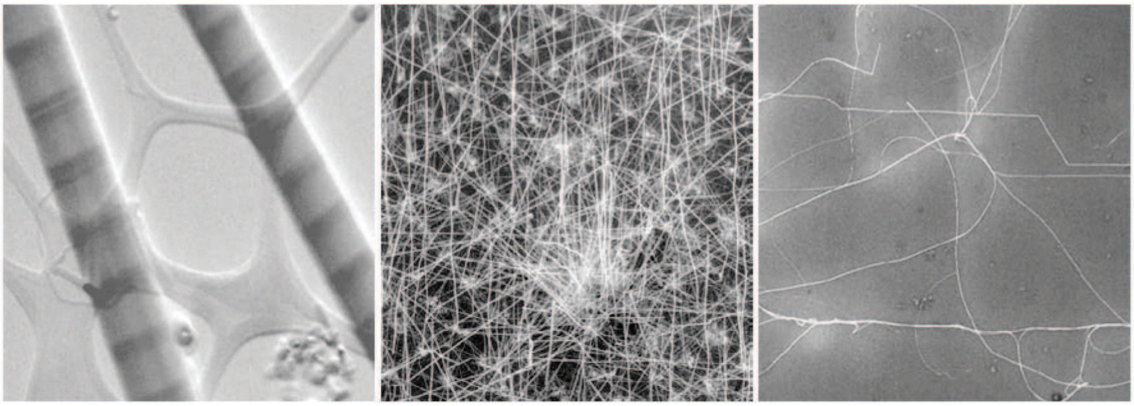
But these "little test pieces" are only half the battle, says Nobel laureate Richard Smalley, professor of physics at Rice. "One has to be able to develop ways of having the [pieces] go of their own volition to where you want them." Billions, even trillions, of molecular transistors could fit on a chip—far too many to arrange one by one. Adds Mark Ratner, professor of chemistry at Northwestern University, "You want this to become so automatic that any bozo can do it."

One of the most promising approaches is called "self-assembly" and hearkens back to biology. "Nature already does a wonderful job" of assembling molecules and other nanoscale components in complex patterns, says **Angela Belcher**, a chemist at the University of Texas at Austin. Belcher is growing multiple generations of viruses and bacteria, seeking to evolve traits such as "protein handles" that would bind with carbon nanotubes—pipelike molecules prized for their strength and electrical properties—and deposit them in patterns useful for nanoelectronics. Learning how to grow nanoelectronics this way may take a while, says Belcher. But a functional nanoelectronic device "seems a lot closer than it was supposed to be a couple of years ago."

It's this new promise that has sparked the rash of startups in the field. "A lot of VCs and investors are looking for the next great waves," says Steven Jurvetson, a venture capitalist at San Francisco-based Draper Fisher Jurvetson and member of the 1999 TR100. "Nanotechnology is one of the great technology opportunities with wide applicability." Jurvetson counts in his company's portfolio three nanoelectronics concerns. And his firm isn't alone. According to VentureSource, venture capitalists invested over $100 million in nanotech-related startups in 2001. But, Jurvetson says, investors should beware. "The prefix 'nano' shouldn't follow the same blind enthusiasm as the '.com' suffix did," he says.

Indeed, for the moment, conventional microelectronics companies have nothing to be afraid of. But the recent advances in nanotech have many researchers convinced that they have a fundamentally new technology on their hands, one that will greatly expand the possibilities of electronics. One important thing to remember, says Bell Labs' Rogers, is that the most eagerly awaited applications may not be the ones that eventually help change how people live. "The people who invented the transistor probably did not imagine a laptop computer," he says. "It's just hard to anticipate these things."

Nanoelectronics is very much in its infancy, and researchers like Schön and Tour freely acknowledge that they are still uncertain where it will have its initial impact. But at least people are now paying attention to—and even investing in—the possibilities. TR



Getting wired: The University of California, Berkeley's Peidong Yang is developing novel silicon nanowires (right) for use in sensors. Projects include doping the wires with germanium (left) to modify their electronic properties and assembling large numbers of intersecting wires (center).

COURTESY OF PEIDONG YANG

TRANSPORTATION

RESEARCH ON EVERYTHING FROM SMARTER ENGINES TO HIGHWAY NETWORKS IS ALL ABOUT INFOTECH. BY DAVID TALBOT

Looking at the progress he and his colleagues at the General Electric Global Research Center in Niskayuna, NY, are making, computer scientist Rusty Irving believes that before the decade is out, jet engines and diesel locomotives will diagnose and report mechanical problems without human intervention.

Sound far-fetched? Consider that these sensor-riddled machines already transmit performance data via satellite to maintenance crews, who look for subtle changes in pressures, temperatures and fuel flows that could mushroom into mechanical breakdowns. "The next level of this technology is to push this intelligence to the unit itself, let it say, 'Hey, I'm not feeling well. I think my problem is *this*; please take a look,'" says Irving.

This desire—to bring enhanced intelligence to transportation systems through information technologies—drives much of today's research and development in the world of planes, trains and automobiles. Cheaper sensors, faster microprocessors, new generations of wireless communications and ever improving software—whether speech recognition for hands-free car phones or complex virtual-traffic models for creating congestion forecasts—make this infotech makeover of transportation feasible; the pressures on existing infrastructure make it necessary.

In some cases, the transition has already begun. Take highway "toll tags." Velcroed to the windshields of many cars, they broadcast account numbers when hit with blasts of radio energy at tollbooths, and they also help count cars along the highway. Near the borders of some states, other tag readers help inspectors identify passing trucks and check their safety records. And in a quintessentially American adaptation, some southern California fast-food joints are even beginning to use them to debit purchases from drive-in customers' accounts.

To piggyback on tag technology, Paul North, a program manager at the Johns Hopkins University Applied Physics Laboratory in Laurel, MD, is developing Web-accessible databases containing truck safety records that can be updated in near real time by federal and state officials. When a truck pulls into a roadside inspection station—or even before it arrives—these databases can be accessed using its tag number. "The idea is to make data available in a very timely, efficient and consistent way, not only to the inspectors, but to the trucking companies and their insurance companies," North says. These Web-based databases should be implemented in the next two to five years, even at the most remote weigh stations, North says.

Toll tags linked to databases are only one example of how wireless technologies are transforming transportation. A growing number of drivers are using "telematics"—the marriage of wireless communications, computing and satellite-based Global Positioning System technologies—to navigate, find local services, check e-mail and even obtain remote diagnoses of car trouble through embedded sensors. Some two million drivers already use such systems—most commonly, General Motors' OnStar service.

Even as these technologies get deployed today, a host of auto suppliers and startups are competing to provide future generations of telematics services with faster data connections, better voice recognition and wider market appeal. Delphi of Troy, MI, has a prototype that uses faster wireless-communications protocols and speech recognition software and could slide into standard automotive radio slots. The device bristles with telematics features such as hands-free voice dialing, Internet browsing and satellite

radio. Far from an exotic luxury add-on, "this is the telematics that can get into every car," says Bob Schumacher, general director of Delphi's mobile-multimedia business group.

There will soon be more infotech under car hoods, too. Carmakers worldwide are competing to incorporate sophisticated, computer-controlled electronic actuators into everything from electromechanical valves to steering and braking devices that could replace traditional hydraulics and mechanical linkages. Systems from companies like Toyota Motor, Honda, BMW and DaimlerChrysler should be among the first to reach showrooms within the next several years.

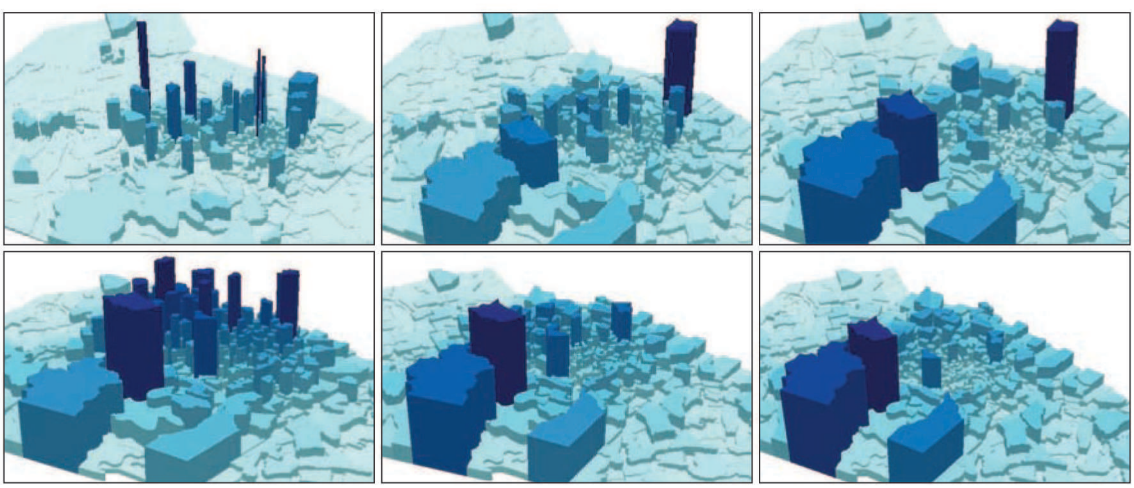
In the aeronautics industry, a communications overhaul could help optimize flight patterns without compromising safety. This would mean gradually supplanting old-fashioned radio links, which only allow voice communication, with robust data links delivering torrents of information—from weather data to the locations and identities of nearby planes—so that cockpit computers can chart the best routes and provide collision avoidance instructions. While forerunners of such systems are today used only in radar-lacking regions like Alaska, in the long run "there will definitely be a move to more satellite-based air traffic control," says John Hansman, professor of aeronautics at MIT and a TR100 judge. "There is already a gradual transition to satellite-based systems over oceans and unpopulated regions of the world, like western China." Still, he says, implementation of such systems for commercial air traffic in developed areas will require overcoming "a lot of nitty-gritty technical and political problems."

Andrew Barrows, president of Palo Alto, CA-based Nav3D, is one of the people trying to overcome those problems. He is developing a cockpit display technology that merges satellite location data with stored information about the earth's surface to produce a virtual view of the ground even in bad weather. For him, the "nitty-gritty" work means further pushing the software to establish the extraordinary accuracy and near perfect reliability required to obtain Federal Aviation Administration certification.

Information technologies are also improving the way the air-, rail- and roadways on which we travel are managed. **Kara Kockelman**, a civil engineer at the University of Texas at Austin, builds computer simulations using data on where people live, how they move around and even their shopping habits to develop new transportation solutions—which corridor would benefit most from a new light-rail system, for example. "Improving highway traffic systems, optimizing rail schedules and even improving manufacturing processes comes down to being able to consider all the options and choose the best one"—a job best done through such modeling, she says.

Sophisticated traffic simulation models can make more accurate predictions by using data on how drivers behave when behind the wheel, according to **Der-Horng Lee**, a civil engineer in Singapore. He is developing algorithms that recognize how different drivers react differently to news of a traffic jam: some stay passively on the road, others take the long way around, others cut through city streets. If such behaviors are accurately reproduced using computer-generated scenarios, Lee says, planners can respond to real jams by, for example, adjusting traffic light sequences on side streets.

For some of these technological possibilities, the only remaining obstacles are human. "As the complexity and information flow in these systems increase, the human will become—or in some cases already has become—the limiting factor in the design and operation of the system," Hansman says. Which may explain why GE's Irving is striving to take us out of the equation. Even as he works on self-diagnosis for jets and trains, Irving envisions machines performing self-repair on the fly—literally. "This is really out-there stuff, but this is the long-range vision," he says. And if the collective computer-centric predictions of researchers like Irving pan out? Getting from here to there will become easier and safer. TR



COURTESY OF KARA KOCKELMAN

Austin, 2067: Projected shifts in where people work (top row) and where they live (bottom row) in segments of greater Austin, TX, in 2007, 2037 and 2067 (left to right) help researchers at the University of Texas at Austin plan optimal regional transportation systems.

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MIT'S MAGAZINE OF INNOVATION
TECHNOLOGY REVIEW

TR100/2002

All hail the TR100! These 100 brilliant young innovators—all under 35 as of Jan. 1, 2002—are visitors from the future, living among us here and now. Their innovations will have a deep impact on how we live, work and think in the century to come.

THE YOUNG INNOVATORS WHO WILL CREATE THE FUTURE
TR100

This is the second time *Technology Review* has picked such a group. The first was in 1999, our magazine's centennial year. That was a wonderful experience, but we've learned a lot in the last three years, and we think this installment is even more exciting than the first.

For one thing, we've chosen a special theme for this version of the TR100: transforming existing industries and creating new ones. We looked for technology's impact on the *real economy*, as opposed to the now moribund "new economy." The major hot spots where we think a fundamental transformation is in progress include information technology, biotechnology and medicine, nanotechnology and materials, energy, and transportation. The bulk of the TR100, who are profiled in the following pages, come from those five areas. These innovators are first grouped alphabetically and then indexed by their areas of work *(p. 95)*.

In addition to this offering in our magazine, we've posted an augmented version of the TR100 special section on our Web site, with more information about all the honorees and a rich set of links to sites pertaining to their original research (www.technologyreview.com/tr100/feature). Choosing this group has been a painstaking process that began more than a year ago. We could not have succeeded without our distinguished panel of judges *(p. 97)*. But it's been worth it. We promise that as you watch the careers of these 100 people unfold, you will be able to accompany them back to their home: the future. TR

ADEKUNLE ADEYEYE | AGE 33

NANOTECHNOLOGY

NATIONAL UNIVERSITY OF SINGAPORE

Ten years ago, Adekunle Adeyeye left his computer-programming job in Ibadan, Nigeria, to get a master's in microelectronics engineering at the University of Cambridge in England. Despite a rocky start, he finished atop his class. He joined the physics PhD program at the university's Cavendish Laboratory, where he researched magnetism in thin films. He then became the first Nigerian elected as a prestigious junior research fellow of Trinity College at Cambridge. There, Adeyeye devised nanofabrication techniques that allowed him to create novel nano magnets. His mentor, physicist Stephen Julian, attributes Adeyeye's success to "tremendous energy and creativity." Today Adeyeye is a founding researcher at the $10 million Information Storage Materials Laboratory at the National University of Singapore, where he works in the field of "spintronics." Conventional electronics take advantage of the charge of electrons in semiconducting materials. But electrons also have a property called "spin." If Adeyeye succeeds in better utilizing electron spin, he could help revolutionize memory and logic devices, leading to smaller, faster and less power-hungry computers.

DOUG BARLAGE | AGE 32

NANOTECHNOLOGY

INTEL

When he was 10, Doug Barlage started making electronic toys with store-bought transistors. Now at Intel, he is building the world's smallest, fastest transistors for future computers. In particular, he has improved the devices' gate oxide—a thin layer that prevents transistors from leaking current but limits their size and speed. Intel's latest version is just three atoms thick. Until Barlage came along, researchers struggled with how to determine the electrical properties of materials so thin; some thought it pointless. Barlage forged ahead, getting more performance from advanced measuring tools than their manufacturers thought possible. "We drove right through the stop sign," he says. The results allowed Barlage to build the optimal gate-oxide configurations. Using designs made possible by Barlage's measurements, Intel has twice set the world record for transistor size and speed, and a third record is close at hand. Coworkers describe Barlage as "meticulous and driven" as he explores just how far he can push transistor technology. "We're probing the physical barriers," he says, "but haven't seen any limits yet."

CHRISTOPHER AHLBERG | AGE 33

SOFTWARE

SPOTFIRE

No pictures adorn Christopher Ahlberg's office. The Swedish-born computer scientist and amateur kickboxer says simplicity encourages people to do what's needed and move on. This philosophy pervades his company, Spotfire. Its DecisionSite software allows computer users to go into multiple databases regardless of their format, easily import, export and manipulate very large data sets, and visualize the results in dynamic graphs, charts and plots. In other words: get the information they need and get out. More than 400 biotech, pharmaceutical, oil and gas, chemical, and auto companies—from Merck to Saab—now use DecisionSite to help them render verdicts on everything from scientific experiments to manufacturing lines. Founded in 1996 by three people, the privately held company now employs 175 in Somerville, MA, and Göteborg, Sweden. Ahlberg has grander designs for DecisionSite, too. Chief among them: becoming the one application companies use to interrogate databases around the world over the Internet, as simply as they navigate text documents on the Web.

ANDREW BARROWS | AGE 34

TRANSPORTATION

NAV3D

For years, researchers have dreamed of improving air traffic safety and efficiency by giving pilots a real-time 3-D display that shows how to navigate terrain, even in bad weather. But merging Global Positioning System data with graphical displays of the earth's surface proved dauntingly expensive. As a PhD candidate in aeronautical engineering at Stanford University, Andrew Barrows delivered the first practical, inexpensive "highway in the sky." He did it by writing software that merges GPS location information with images from terrain databases and shows the pilot a series of rectangles. The pilot need only keep the plane flying through these targets. "Fifteen years from now, every airplane will have a sophisticated version of this," says John Hansman, MIT professor of aeronautics and astronautics. While the Federal Aviation Administration works on certifying this type of system, Barrows has left academe to become president of Nav3D in Palo Alto, CA. One big client, Boeing, is adapting his technology for military use. Nav3D is also exploring displays that would help construction crews "see" underground gas lines or guide firefighters through smoky buildings.

ANGELA BELCHER | AGE 34

NANOTECHNOLOGY

UNIVERSITY OF TEXAS AT AUSTIN

Angela Belcher "fell in love" with molecules as a college freshman. As a doctoral student at the University of California, Santa Barbara, she answered provocative questions that fused the biological and physical sciences. Chief among them: could proteins sculpt the structure of semiconductors? Belcher identified a series of proteins that bind to semiconducting nanoparticles and used them to help direct the assembly of the nanoparticles in ways not possible before. Belcher and her postdoctoral advisor, Evelyn Hu, formed a company, Semzyme, based in Santa Barbara, CA, to create such protein tools. Now at the University of Texas, Belcher says her passion for science remains so intense that she often wakes at 2:00 a.m. ready to head to the lab. Recently, her team discovered a novel way to make liquid crystalline films. Belcher is also using proteins loaded with semiconductors to help create nanoscale "quantum wires" for tiny electronic components. Belcher plans to continue her research this fall as an MIT professor.

RICHARD BARTON | AGE 34

INTERNET AND WEB

EXPEDIA

In 1994, Richard Barton devised a plan to revolutionize the travel industry. He convinced Bill Gates, his boss, that online travel planning had a future and in 1996 launched Expedia. In 1999, Barton spun the company off from Microsoft and has since grown it into a thriving dot com. Today the site receives queries from 15 million people a month. In February, USA Networks—which owns Ticketmaster and Citysearch—acquired majority interest in Expedia for more than $1.3 billion. Barton, who helped develop the MS-DOS 5.0 and Windows 95 operating systems, says, "Our competitive differential is all about technology." Under his leadership as chief executive officer, Expedia developed an award-winning algorithm that compares prices on billions of flight combinations and allows customers to find and buy the lowest fares. Barton now wants to make the customers' transactions even easier and more secure while customizing services to each person's buying habits. "Helping people take a trip is fundamental to our long-term dream," he says.

ELIZABETH M. BELDING-ROYER | AGE 27

TELECOMMUNICATIONS

UNIVERSITY OF CALIFORNIA, SANTA BARBARA

Today's mobile data networks are spotty. If you're not within range of a transmitter or are cut off by large obstacles like skyscrapers, you're out of luck. The solution could be networks that form only when needed, and Elizabeth M. Belding-Royer may deliver them. As a graduate student at the University of California, Santa Barbara, Belding-Royer worked with Nokia research fellow Charles Perkins to develop the necessary network protocols—the operational instructions. If your handheld device finds itself with a nonexistent or failing signal, it can use Belding-Royer's protocols to find and connect with nearby wireless devices. These neighbors then find a path through still other wireless devices to create an ad hoc but solid connection. Designing the protocols helped Belding-Royer land a professorship at UC Santa Barbara, and the Internet Engineering Task Force is now considering turning them into standards. Applied, the protocols could eliminate "dead zones" that wireless transmitters don't reach and make it cheaper and easier to set up networks everywhere—from the Sahara to downtown Los Angeles.

VINCENT BERGER | AGE 33

TELECOMMUNICATIONS

THALES

Vincent Berger has two jobs, two labs, even twin babies. As a researcher at Paris-based aerospace giant Thales, he developed the technology behind a new short-wavelength night-vision camera for military surveillance. But he's best known for his theoretical contributions in optical semiconductors, quickly becoming a linchpin of telecommunications. At 29, Berger was the first to describe ways to integrate photonic crystals with bulky optical devices such as routers. Many think this work will lead to wafer-thin chips that can manipulate photons the way semiconductors control electrons. He was also first to demonstrate that light waves could change color in gallium arsenide, the superfast material of choice for the ubiquitous semiconductor laser. While others convert Berger's theories into technologies such as miniature cryptography devices, telecom traffic busters and air pollution detectors, he is busy balancing his position at Thales with his new role as university professor. He looks forward to forging industry-university partnerships—not often found in France—to boost the commercialization of photonics research.

ERIC BONABEAU | AGE 34

SOFTWARE

ICOSYSTEM

Bugs can improve business. So says theoretical physicist Eric Bonabeau, who has spent 10 years watching ants and wasps to understand "swarm intelligence." He derives rules from their complex behavior and applies them to optimize telecom network routing and gasoline pricing. A French citizen, Bonabeau studied biology and physics before being hired in 1990 at France Telecom to improve network intelligence. When he approached managers with ideas based on insects, they ignored him. He left in 1996 to become a research fellow at the Santa Fe Institute in New Mexico, where he studied the behaviors of insect colonies, including how ants self-organize to find the most efficient paths to food. The key, he says, is spotting the "emergent behavior" of the colony. In 1999 he started consulting company Icosystem in Cambridge, MA, which has worked with BP, Eli Lilly and Unilever. Using Bonabeau's ant-based algorithms, Southwest Airlines revised work procedures and the flow of baggage in its cargo-handling process. The scheme cut package transfer rates by 70 percent at busy hubs, saving the company millions of dollars.

EWAN BIRNEY | AGE 29

BIOTECHNOLOGY

EUROPEAN BIOINFORMATICS INSTITUTE

Think of the human genome as Tolstoy's *War and Peace* in the original Russian—immense, exciting, but for most, indecipherable. British bioinformatician Ewan Birney wants to make the genome's information accessible to all. His Ensembl software and data allow researchers to find information on the Web on any known or predicted gene and to automatically match pieces of genes they have sequenced with other genes—without tediously combing through endless raw-sequence data. Cofounded by Birney, the Ensembl project has become one of the most popular resources for genome research, and its software is freely available to use and modify. With his related work adapting programming languages such as Perl and Java to biological projects, Birney has become a force in the bioinformatics open-source community. "In bioinformatics" he says, "the software is actually not that important. What's much more important is the data." Birney's ambitious tools will help researchers deliver on the promise of new drugs and treatments derived from the Human Genome Project.

STEPHEN BOPPART | AGE 33

MEDICINE

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

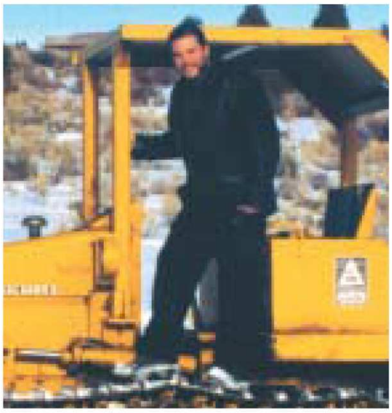
Stephen Boppart grew up in Illinois farm country, where he acquired a get-things-done attitude. His master's-degree advisor says, "The speed with which he can conceptualize, test and implement is remarkable." While simultaneously completing a PhD in medical and electrical engineering at MIT and an MD at Harvard, he published 44 peer-reviewed papers and book chapters. During those seven years, Boppart helped dramatically improve the resolution of optical-coherence tomography, an imaging technique that sends near-infrared laser light into a person's tissues and then interprets its reflection from structures within. Boppart also converted the hardware into a handheld probe that looks like a laser pointer. Surgeons at Brigham and Women's Hospital in Boston are using it to see through a patient's skin before making an incision. Recently Boppart received funding from the Whitaker Foundation, the National Cancer Institute and NASA to determine how to use optical-coherence tomography in cancer diagnosis. He is now developing contrast agents, such as carbon and melanin, that will increase a tumor's resolution when seen using this technique.

DANIEL BRANAGAN | AGE 33

MATERIALS

IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

When most people speak of advanced materials, they mean semiconductors or biopolymers. But Daniel Branagan means steel. The materials scientist is transforming metals industries with his new "superhard steel." His novel process rapidly cools molten steel into a glasslike solid, then heats the solid to form a unique nano structure. The result is a coating that outperforms the hardest metal coatings, even tungsten carbide, at one-third the price. Superhard steel is cheap and easy enough to manufacture that applications could range from rock crushers to kitchen knives. More than 500 companies have expressed interest in using Branagan's material to make tougher, lighter, longer-lasting products. Branagan may license the patent from the U.S. Department of Energy—which oversees his lab—to create a spinoff company. The Michigan native launched his career 12 years ago by developing tougher rare-earth magnets for computer hard drives. But while other metallurgists tout Branagan's innovations as feats of nanoscale engineering, to this ranch owner outdoorsman they're "just fancy steels."



ARNAUD BRIGNON | AGE 33

HARDWARE

THALES

Lasers are found in everyday products, from compact-disc players to bar code readers. But in a laser beam strong and focused enough to shoot down an enemy aircraft or chisel pin-sized mechanical parts out of metal blocks, the hyperexcited photons have to be controlled so they don't scatter. Improvements on solid-state lasers have been stymied by the tendency of a beam to distort as the crystal at the heart of a laser heats up. Arnaud Brignon, who was born eight years after the laser was invented in 1960, has solved this problem by developing a self-correcting mirror made from nonlinear crystals that cancels the distortions. His division of multinational aerospace giant Thales, in Orsay, France, is identifying markets for commercial versions of the laser, which Brignon says could be ready in three years. While working on a next-generation laser, Brignon finds time to hunt for dinosaur remains in the fields of France. He recently discovered a tooth from a 100-million-year-old armored ankylosaur that was previously undocumented in his country.

FIONA BRINKMAN | AGE 34

BIOTECHNOLOGY

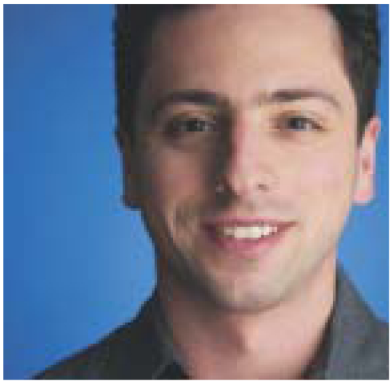
SIMON FRASER UNIVERSITY

Pathogens often exploit our cells to thrive. Fiona Brinkman therefore hypothesizes that some of their genes are similar to human genes. By identifying such genes computationally, Brinkman is trying to understand how drugs could stop pathogens from storming the body's fortress. Brinkman coordinates this interdisciplinary work through an online "pathogenomics" project she runs from Simon Fraser University in British Columbia. It uses a free program she developed called PhyloBlast to evaluate relationships between genes by comparing their sequences and the proteins they code for. Previously, Brinkman organized the first Internet-based effort to refine and annotate bacterial genome data, focusing on *P. aeruginosa,* a widely drug-resistant bacterium that causes fatal infections in cystic-fibrosis patients. The group gained critical insight into how the bacterium works, which had eluded researchers. "Once we have the parts list for how the bug is functioning," Brinkman says, "we can figure out new approaches to drugs." Her collaborative electronic approach is now being used by other genome researchers.

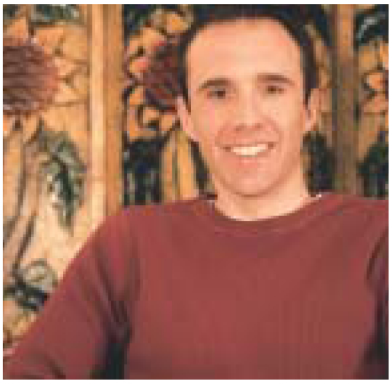
SERGEY BRIN | AGE 28

INTERNET AND WEB

GOOGLE



Today's World Wide Web is a jungle. How to speedily and smartly sort through it? More than 150 million times a day, users turn to Google, the four-year-old search engine developed by a pair of Stanford University graduate students. Sergey Brin and Larry Page *(p. 84)*, PhD candidates in computer science, often found themselves stymied when hunting for data. "Innovation in search had halted," recalls the Russian-born Brin, who had been researching data mining. Brin and Page dropped their doctoral work and came up with PageRank. The software measures the importance of a given Web page by how many other pages link to it—and by how important those linked pages are. As soon as Mountain View, CA-based Google went live in 1998, it attracted Web surfers who wanted rational search results. Today nobody lists as many Web pages (over two billion) or sorts them as fast (a typical search takes under a second). Now that Google is a success, Brin, once known as a jokester, says he has turned serious. "Jokes are no longer allowed—that's what our PR people tell me," the copresident says.



STEPHEN BROSSETTE | AGE 30

MEDICINE

MEDMINED

Although he's a doctor, Stephen Brossette thinks he can save more lives by using technology than by seeing patients. As a University of Alabama at Birmingham graduate student, Brossette developed a mathematical technique for finding subtle, otherwise unnoticed patterns in medical data. His approach can reveal an impending outbreak of a hospital-borne infection by identifying patients who share similar demographic backgrounds, frequent the same hospital rooms and have the same odd microorganisms in their lab cultures. In 2000, Brossette formed MedMined in Birmingham, AL, to market his innovations. The company currently has eight employees serving as many hospitals. They sift through masses of data provided by the hospitals to uncover patterns of nascent antibiotic resistance and outbreaks of infectious pneumonia, diarrhea and other diseases. Brossette says early detection can improve intervention—vital because two million patients acquire infections in U.S. hospitals each year, and 90,000 of them die. The amateur photographer and Cajun/Creole chef is also analyzing how best to apply his tools to bioterrorism and contaminated foods.

CHRIS BURGE | AGE 33

BIOTECHNOLOGY

MIT

Chris Burge admits it's been hard to choose a research focus. In high school he won math contests but in college majored in biology. He traveled to Nicaragua to see if medicine was his calling but wound up teaching people there about computers. He finally settled on the interface between biology and mathematics and returned for graduate study in math at Stanford University, his alma mater. The sophisticated computer program he developed there, called Genscan, predicts the locations of genes in the human genome and what proteins they produce. Released in 1997, Genscan is the most popular program of its type. Geneticists and molecular biologists are using it to identify human disease genes and potential drug targets and are applying it to agriculture. It is available free on the Web for nonprofit use and has been licensed to dozens of companies. Now at MIT's biology department, Burge has developed a companion program, GenomeScan, that compares known proteins to increase the accuracy of Genscan predictions. He hopes to answer fundamental questions that could shed light on how human genes are expressed.

JOHN CARMACK | AGE 31

ENTERTAINMENT

ID SOFTWARE

For a decade, John Carmack, cofounder of id Software, has revolutionized the computer game industry with immersive first-person shoot-'em-up games where players maneuver through 3-D worlds as characters on the screen. Since 1992 the self-taught programmer has attracted a devoted following of millions and has broken sales records with Wolfenstein 3-D, Doom I and II and the three-part Quake series. His work raised the standard from simple games to complex, role-playing scenarios, which are so compelling that the U.S. Marines have used the games to train fighters. To make possible more realistic environments, Carmack has used leading-edge graphics hardware to create game engines, and he freely allows developers to improve them. "A great many people in the industry got their start modifying our games," he says proudly. Carmack—who also builds small rocket-powered vehicles—and his crew in Mesquite, TX, are working on a new engine that improves the depth and texture of 3-D environments. His ultimate goal: achieve a level of rendering equal to those "of film and television graphics."

JOSEPH CARGNELLI | AGE 32

ENERGY

HYDROGENICS

Hydrogen fuel cells promise to break the world's fossil fuel habit without a puff of carbon dioxide, and Joseph Cargnelli is helping them deliver. In 1995, from a small room above his family's machine shop in Toronto, Ontario, the mechanical engineer and two associates launched Hydrogenics. The company made its mark producing test stations Cargnelli designed and assembled to put fuel cells through their paces. The test units accelerated the work of fuel cell developers and secured Hydrogenics' $84 million initial public offering in 2000. Today Cargnelli, vice president, is worth millions. But the roar of equipment still fills his shop floor office at a complex on Toronto's west side, where Hydrogenics is developing its own fuel cell engines. Last year, in a six-month span, Cargnelli's team prototyped a fuel cell generator and transformed it into a backup power supply to keep cell tower antennas and their networks alive during blackouts. This work clinched a partnership with General Motors. To Cargnelli, success just means one more step toward the hydrogen economy.

HOWIE CHOSET | AGE 33

HARDWARE

CARNEGIE MELLON UNIVERSITY

Howie Choset built himself a "snakebot" named Schmoopie, but that's not what sets him apart from colleagues. The mechanical engineer and roboticist has developed motion-planning algorithms that ensure his autonomous, multi-jointed snakes not only sense and respond to objects in their path but explore every nook and cranny as they traverse a terrain. Other path-planning algorithms leave room for ambiguity, but Choset's provides for complete coverage. As a result, the U.S. Office of Naval Research is funding Choset to build robots that search for buried mines. Choset has equipped his bots with mine detectors; when they sense a mine, they map its location, then maneuver around it. Choset is also working with Ford Motor to develop robotic car-painting techniques that will save production time. During it all, he has developed the robotics minor at Carnegie Mellon University and says, "I would like to see this work get to the high-school and junior-high level and have students build robots to learn basic math and physics." Choset also hopes his algorithms and theories will one day be used in non-robotic applications, such as predicting crime patterns.

BURGE: FURNALD/GRAY

BENJAMIN CRAVATT | AGE 31

BIOTECHNOLOGY

SCRIPPS RESEARCH INSTITUTE

Chemical biologist Benjamin Cravatt is developing tools to illuminate the roles of proteins and enzymes in humans and animals. Cravatt and colleagues have synthesized dozens of fluorescent probes that chemically bind to enzymes in laboratory samples of healthy and diseased tissues, then light up when excited by a laser scanner. The technique can show which enzymes are more or less active in cancerous cells, which could herald a breakthrough for proteomics—the attempt to identify the structures and functions of human proteins. Cravatt's protein-activity-based approach represents an advance over methods that merely infer protein function by comparing the abundance of proteins in samples. His technology also forms the basis of ActivX Biosciences in La Jolla, CA, which he cofounded in 2000 and now employs more than 40 people. Applications for the chemical probes include improving medical diagnostics, identifying new drug targets and facilitating drug tests. "Helping with the development of a single drug would be huge," the hyperkinetic researcher says, "but we hope to do this many times over."

JOSH COATES | AGE 28

SOFTWARE

SCALE EIGHT

Ignore the bare feet. Josh Coates may look like an exuberant techie grad student, but he is a serious business player who has convinced investors to pony up $55 million for his 1999 San Francisco startup, Scale Eight. The chief technology officer has a paradigm-shattering idea that says the right software deployed over the Internet or local networks will let large corporations dramatically cut their data storage bills. Right now, data storage involves expensive, proprietary hard drives that are usually deployed at a few central sites; it's a $20 billion market set to grow inexorably as more computers produce ever more information. But Scale Eight challenges that inevitability. Coates says his software will let customers use networks to route data to scores of cheap, off-the-shelf hard drives, where they can be stored inexpensively and securely. "I'm trying to sweep hardware out of the way and thereby commoditize storage, really lowering the costs," says Coates, who counts Microsoft among his two-dozen customers. "Software has no bounds," he adds. "If you can think of it, you can do it in software."

NATHANIEL DAVID | AGE 33

BIOTECHNOLOGY

SYRRX

Leave it to a structural biologist who thought about becoming a pastry chef to write an industrial-scale recipe for accelerating drug discovery. In 1999, with a doctorate from the University of California, Berkeley, Nathaniel David cofounded Syrrx, the world's first automated factory devoted to analyzing proteins and their interactions with drugs using structural biology. The three-dimensional shape of a protein determines how well a particular drug will bind to it, but the structures of many critical human proteins remain unexplored. It can take researchers in a traditional lab months to produce, purify and crystallize a single protein and confirm its shape. Under David, San Diego-based Syrrx adapted robot arms from automotive assembly lines to crystallize proteins with far greater speed: the company can reveal 11 to 15 structures a month. Some scientists doubted the feasibility of automating an intricate lab process, but David—who claims his best quality as an innovator is stubbornness—prevailed. As sole employee for 16 months, he raised $25 million. Syrrx now has 131 employees, $100 million in capital and has analyzed 90 potential drug targets for three pharmaceutical makers.

PAUL DEBEVEC | AGE 30

ENTERTAINMENT

UNIVERSITY OF SOUTHERN CALIFORNIA

Paul Debevec's rise to computer graphics stardom sounds like a fairy tale. In 1996 Debevec presented a paper on Façade, a system he developed as a student that digitally generates 3-D scenes from 2-D photographs. Soon after, he was flown to Hollywood to present his technology to John Dykstra, the visual-effects supervisor on *Batman and Robin*. Effects companies have since used Debevec's techniques in several films, including *The Matrix*. Debevec now directs the graphics laboratory at the University of Southern California, where he is perfecting the Light Stage. Inside this three-meter-wide spherical structure, actors and objects are illuminated by 156 light-emitting diodes that duplicate light from any environment. For example, an actress can be illuminated with light recorded inside the Sistine Chapel, and her image can be simultaneously superimposed on a scene set there. The technique yields far more realistic results in less time than the standard method of adjusting concocted lighting frame by frame. "The idea is to use the light from the actual scene, rather than manually try to approximate it," says Debevec, who admits to being under Hollywood's spell.

JENNIFER ELISSEEFF | AGE 28

MEDICINE

JOHNS HOPKINS UNIVERSITY

Jennifer Elisseeff is shining light on better ways to repair human tissue. While getting her doctorate in medical engineering from the Harvard University-MIT Division of Health Sciences and Technology, Elisseeff designed a liquid polymer that can keep cartilage cells alive. In patients, the polymer hardens into a hydrogel—a scaffold on which the cells can develop into new tissue. Normally, surgeons have to cut open a patient to insert such a polymer, and shine light on it to induce it to harden. Elisseeff wondered if she could devise a polymer that hardened under minimal light. That way, surgeons could simply inject the compound and shine a light through the skin to trigger solidification, obviating the need for surgery. Her experiments with mice and rats succeeded. Now, Advanced Tissue Sciences of La Jolla, CA, is investigating the polymer as a way to repair everything from ruined knees to facial damage. Meanwhile, Elisseeff is impregnating hydrogels with stem cells—which can mature into different human cells—to try to create a new form of cartilage replacement. "So little is known about stem cells," she says. "It's very exciting."

MICHELLE EFFROS | AGE 33

TELECOMMUNICATIONS

CALTECH

So much data, so little bandwidth. That's the mounting problem Caltech professor of electrical engineering Michelle Effros has wrestled with for 10 years. Her innovations in data compression over networks are so original that Stanford University electrical engineering vice chair Robert Gray calls them "profound." Her heady work has almost single-handedly created research interest in algorithms to optimize transmission of data over busy, noisy networks like the Internet and various wireless infrastructures. At first "it was hard even to get peer reviews of research," she recalls. But Effros persisted. "I like working further out. Entrepreneurism is not what excites me—research into new areas does." Today, however, her algorithms set the standard for academic- and commercial-network compression techniques. And the recreational mountain hiker says with a smile that her once neglected field now teems with breakthroughs. "We are really starting to crack the data compression problem," Effros says. "Progress is coming much faster now."

SHAWN FANNING | AGE 21

INTERNET AND WEB

NAPSTER

Not many undergrads write world-changing code, appear on the covers of *Time*, *Fortune* and *BusinessWeek*, or testify in front of U.S. Senate committees before they can legally buy beer. Shawn Fanning has done all three since founding the cultural juggernaut Napster in a Northeastern University dorm in 1999. Fanning transformed a software script he wrote to help a roommate retrieve digital music files from the Internet into a full-featured online swap service millions of users strong. The free program enabled users to post MP3 digital music files they had on their computers to an online index supported by Napster, and to access files from any other person's computer. That way, users could swap music files directly. The application became so popular that the Recording Industry Association of America effectively shut it down in 2001 through lawsuits alleging copyright infringement. Fanning is busy relaunching his company as a paid subscription service. His concept, though, continues to challenge the status quo. Music industry giants are scrambling to mimic Napster's success on a pay-per-use basis—but to no avail, as free copycat sites constantly spring up.

ALEXANDER FAY | AGE 31

TRANSPORTATION

ASEA BROWN BOVERI

Train buff Alexander Fay jumped at his PhD advisor's suggestion to design knowledge-based software to help human railway-traffic controllers in their struggle to keep trains running on time. When train breakdowns occur, some controllers tinker with track signals to reroute trains; others call for backup trains. Their decisions ripple through the rail system. Studies estimate $200 in lost economic opportunities for each minute a passenger train is late. Given Europe's congested rail networks, the potential savings from better management is huge. After interviewing dozens of controllers, Fay used fuzzy-logic principles to integrate 150 when-this-occurs-do-that rules into his software. German Railways is now implementing his computer program, which standardizes the most efficient responses to service disruptions, in one of its regional control centers. Fay's methods also apply to other systems. At Zürich, Switzerland, construction giant Asea Brown Boveri, he is developing software that captures the know-how of process and control engineers to reduce problems in designing and running pharmaceutical, chemical and energy plants.

JUSTIN FRANKEL | AGE 22

INTERNET AND WEB

AOL TIME WARNER

Justin Frankel has brought music to desktops in numerous ways. After dropping out of college in 1997 and returning home to Arizona, he wrote Winamp, a program that let people play downloaded MP3 music files on their PCs. It was much easier to use than existing MP3 players. He and partner Tom Pepper also devised Shoutcast, which enables computers to broadcast like radio stations over the Internet. To vastly expand music's availability online, Frankel then created Gnutella, a system that lets Internet users swap MP3s and other files. Unlike Napster, Gnutella does not pass files through a central distribution point—and recording companies can't track them. By the time Frankel released Gnutella in 2000, he had sold Nullsoft, the company under which he developed Winamp and Gnutella, to America Online. AOL paid $400 million for Winamp and online-radio pioneer Spinner Networks and merged them under AOL Music in San Francisco. But AOL became wary of Gnutella because it let people acquire music they hadn't paid for and pulled the program. What's next from Frankel? "Just stuff that hopefully will make a difference," the rebel says. That's a tune he's played before.

CLAIRE GMACHL | AGE 34

TELECOMMUNICATIONS

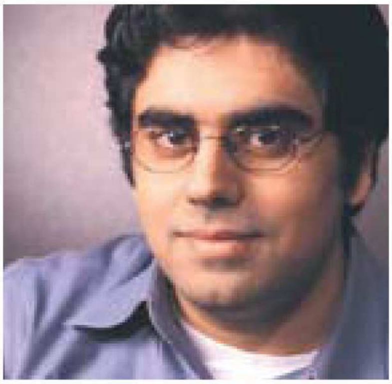
LUCENT TECHNOLOGIES' BELL LABS

Beam mid-infrared light waves across a power plant's smokestack and you can measure the flow of gaseous pollutants. Feed that data back to the plant and you can trim pollution and fuel consumption. It's just one opportunity created by the quantum cascade laser. The laser, invented at Bell Labs in 1994, had promise as the heart of a smaller, less expensive, more efficient apparatus for monitoring smokestack emissions. But when Austrian physicist Claire Gmachl arrived at Bell Labs in 1996, the laser still had one fatal flaw: a messy, broad-spectrum beam. Within a year, Gmachl had the problem licked. She amplified one portion of the beam by sculpting the laser crystal into an echo chamber for photons. It was a major leap, and colleagues say the intense Gmachl has since delivered an average of two advances of similar importance each year. She's also been experimenting with lasers tuned to identify telltale gases found in our breath that may indicate everything from asthma to heart disease. Now Gmachl is focused on carrying data in fiber optics, where rapid-pulse lasers could help sate our hunger for bandwidth.

VINAY GIDWANEY | AGE 20

SOFTWARE

CONTROL-F1



Vinay Gidwaney wrote the software that his Calgary, Alberta, high school used to teach his classmates word processing. Resellers expressed interest, and Gidwaney, only 16, started a small company to supply it. But he found himself spending a lot of time meeting customer requests. Youthfully impatient and eager to reserve his time for writing code, he created software tools to automatically handle certain customer support tasks. Gidwaney soon realized he could develop versions of the software tools to sell to other companies, to enable them to provide live support to their customers over the Internet. So the Canadian started Control-F1 in Calgary. Gidwaney, chief technology officer of the 40-person company, calls his tools "better than being there." That's because a remote customer can continue to work on her computer while Control-F1 software is solving her support problem in the background: no need for her to step away from the computer for a human technician. Several organizations now use Control-F1 to provide customer support, including Novell, Unisys and IBM.

ROBERT GUTTMAN | AGE 32

SOFTWARE

FRICTIONLESS COMMERCE

Choosing a car color is hard enough. Imagine trying to make strategic purchasing decisions for a huge corporation. Robert Guttman's knack for software agents—autonomous, personalized programs that facilitate better-informed decisions—has made such buying chores easier. With an artificial-intelligence degree and four years at Motorola, Guttman arrived at the MIT Media Lab in 1996 to plan the world's first agent-mediated marketplace experiment. His idea was to create software agents that could find certain goods for their masters at preferred prices, then negotiate and close sales on the buyer's behalf. The successful experiment left Guttman wondering whether similar agents could function in real-world marketplaces. In June 1998, along with two MIT colleagues, Guttman founded Frictionless Commerce in Cambridge, MA, to commercialize his technology. The software is now used by operations like the U.S. Army for large purchase orders of laptops, truck brakes, even lumber. With Frictionless's success secure, Guttman has left his post as chief technology officer—though he remains a board member—and is shopping his talents around.

TR100PROFILES

SUSAN HAGNESS | AGE 31

MEDICINE

UNIVERSITY OF WISCONSIN-MADISON

Breast cancer will strike more than 200,000 women in the United States this year, and 40,000 will die. X-ray mammography is the best way to detect early tumors, but the technique misses one in five cases, and women find the test uncomfortable. Susan Hagness and collaborators have invented a better breast-imaging technique. A woman lies on her back so that her breasts flatten naturally, and an instrument Hagness is developing scans the breast tissue with very-low-power microwaves, which are safer than x-rays. Hagness's preliminary measurements on breast biopsy specimens indicate that microwave imaging makes malignant tumors stand out better than x-rays do. The energetic Hagness developed sophisticated computer algorithms—which process data collected by the imaging instrument—to enhance the detection and discrimination capabilities of microwave imaging. So far, her computational studies indicate that her approach should detect tumors just a couple of millimeters across, an improvement on the five-millimeter limit of x-ray mammography. The first version of Hagness's instrument will be used for research.

DEREK HANSFORD | AGE 29

MATERIALS

OHIO STATE UNIVERSITY

Derek Hansford's unobtrusive bearing is just what you'd expect from someone who designs ways to sneak drugs past the immune system. Hansford has been fabricating tiny polymer particles that can hold drugs and be injected into a patient's bloodstream. Once there, they could hunt down tumors and release their drugs, without affecting healthy cells. Along the way, the particles would shield the drugs from degrading enzymes and would not elicit attacks from the immune system—a common problem for cancer drugs—because they do not attract immune cells. Although other bioengineers are making polymer drug-delivery devices, none has made large numbers of uniform particles small enough to travel in the bloodstream; each of Hansford's particles is about the size of a red blood cell. The scientist has adapted a technique called soft lithography to make the particles, casting hundreds of millions of them in varied shapes out of reusable molds. Startup company iMedd plans to license his technology. Hansford will now try to make particles for inhalable drugs—an alternative to injections.

MICHAEL HANSEN | AGE 32

HARDWARE

SARNOFF

As a child, Michael Hansen hung out at Radio Shack and wrote such good programs on the store's computers that the salespeople ran them as demos. Software mastered, he learned hardware, earning a graduate degree in electrical engineering. In 1993 he joined Princeton, NJ-based Sarnoff to tackle visual processing—"the hardest darn problem I'd ever seen." Before he knew it, Hansen, who also found time to become a private pilot, was leading a $5 million-a-year group. In 2000 his team developed a chip that lets inexpensive portable devices process visual data collected by surveillance cameras. The chip provides hundreds of times more visual processing than a general-purpose Pentium microprocessor at one-tenth the cost, says Peter Burt, director of the vision technologies lab at Sarnoff. The for-profit R&D company believes networks of such simple devices will have great commercial value in military surveillance, law enforcement and auto safety. In order to, as he puts it, "shorten the path from technology development to new products," Hansen is now working on his MBA.

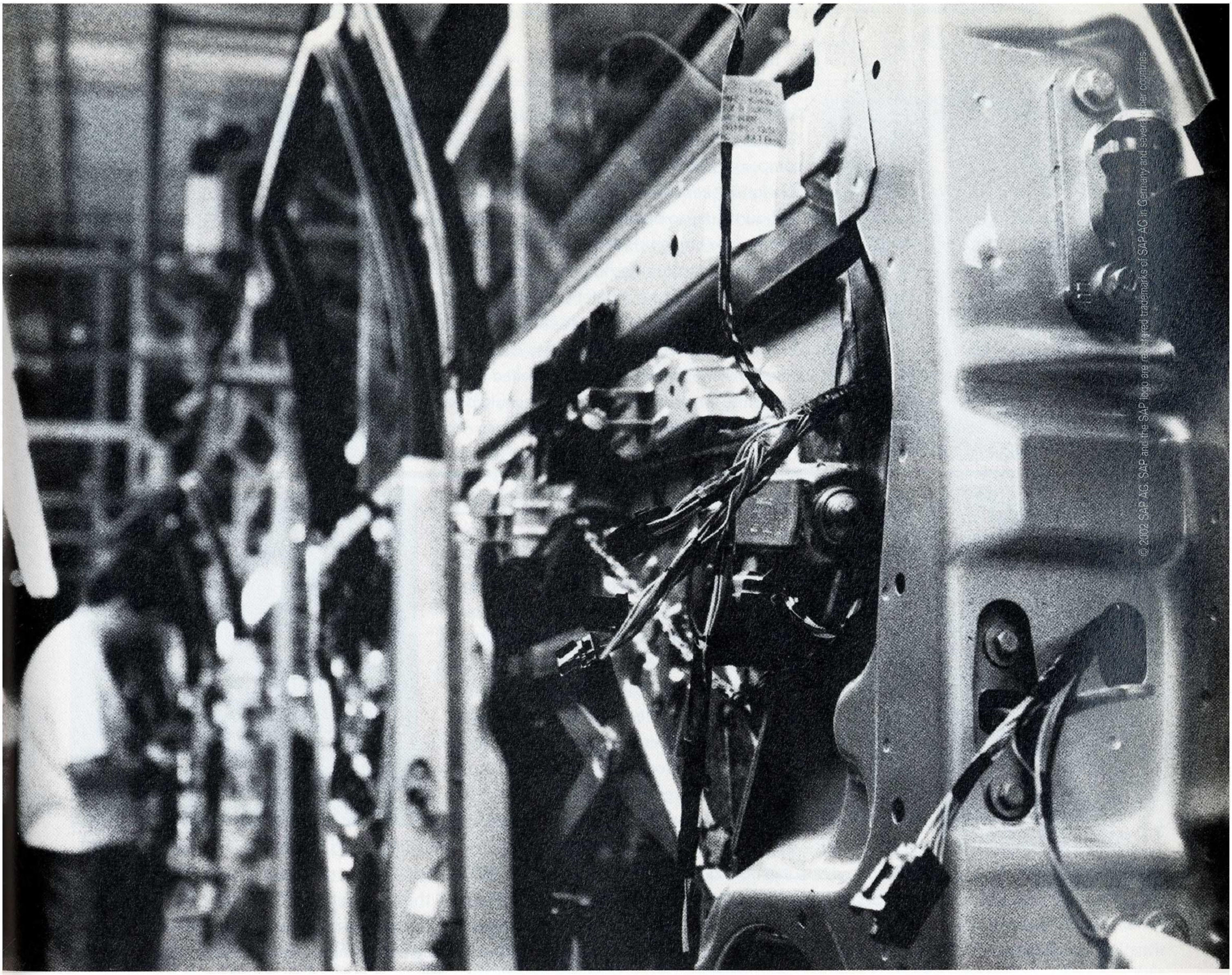
RAMESH HARIHARAN | AGE 32

SOFTWARE

STRAND GENOMICS

In school, Ramesh Hariharan found biology boring. But once he became a computer science professor at the Indian Institute of Science, he got excited about the race to map the human genome. So he cofounded Strand Genomics in Bangalore, where he designs software tools to efficiently analyze the ever increasing volume of data about the makeup of genes. One U.S. customer is applying Hariharan's data-crunching innovations to proteomics—the analysis of protein structures to aid in the discovery of new drugs. Strand Genomics expects to grow from 35 to 100 employees this year. Wearing another hat, Hariharan also works to bridge the digital divide. With colleagues from the university and from a local software firm, he started the nonprofit Simputer Trust to develop a simple, cheap (under $200), portable, battery-operated computer to bring the Internet to the developing world. The trust's first targets are rural Indian village schools, hospitals or community centers that have phone lines. Villagers get smart cards that give them access to a shared Simputer, while touch-screen icons and the Dhvani text-to-speech system Hariharan developed empower illiterate users.

HARIHARAN: CHRISTOPHER BROWN/CORBIS SABA



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JOHN HARRINGTON | AGE 34

MEDICINE

ATHERSYS

Growing up in the shadow of Amgen in Thousand Oaks, CA, and then working in the company's labs during college, John Harrington saw what it takes to succeed in biotech's upper echelon. He kept that in mind when he founded Cleveland-based Athersys in 1994, then worked 18 hours a day to build it while still a postdoc. During that time Harrington coinvented the first man-made human chromosome; gene therapists are now investigating how to use such artificial chromosomes to penetrate cells and repair disease-causing genes. In his academic work, Harrington discovered fen1, a DNA-cutting enzyme that can accelerate the spread of cancers. Athersys is pursuing drugs that inhibit fen1 because they have the potential to treat cancer, alone or with chemotherapy. Athersys's 130 employees are also commercializing Harrington's most recent invention, a process called "random activation of gene expression," which unveils the functions of proteins and could be an important tool in medical research and therapy. Athersys investors seem happy with Harrington's creations and his ability to go all out: since 2000 they have chipped in $90 million.

TRAVIS KALANICK | AGE 25

INTERNET AND WEB

RED SWOOSH

Travis Kalanick is good at escaping sticky situations. In 1998, he launched Scour.com with six buddies at the University of California, Los Angeles. What began as a Web search engine morphed into a popular peer-to-peer file exchange system with 250,000 simultaneous users trading movies and music. Everything was looking up until more than 30 media companies sued Scour for $250 billion for copyright infringement. Scour settled and eventually sold its assets. Then, in 2001, Kalanick founded Los Angeles-based Red Swoosh with Scour's engineering team. They've developed software that streamlines the way content—documents, music, videos—is moved around on the Internet. Typically, when you request a file from a Web site, it is delivered from a centralized server. Red Swoosh's software continually updates a directory that lists which files are on which servers and end-user desktops and transfers the file to you from the closest source, speeding delivery. The scheme also saves big bucks in server infrastructure for the company that posted the file. Several media moguls with busy Web sites are now testing his software.

MAR HERSHENSON | AGE 30

SOFTWARE

BARCELONA DESIGN

Mar Hershenson came to Silicon Valley from Barcelona, Spain, for a summer job, met her future husband and stayed, bringing a bit of her native city to California in the form of Barcelona Design, which she cofounded in 1999. The Sunnyvale, CA, company produces software and intellectual property, developed by Hershenson, for quickly optimizing the design of analog circuits for cell phones, TVs and DVD players. Previously, engineers could spend a year designing a single analog chip. With Barcelona's solution, custom analog circuits can be finished in hours. Hershenson's breakthrough was to represent circuits with equations that can be solved mathematically. She learned the technique in a course taught by Stephen Boyd, the Stanford University professor with whom she launched the company. The 45-employee firm has raised $44 million and lined up several large clients, including chip-making giant STMicroelectronics. Bursting with ideas, Hershenson plans to apply Barcelona's technology to a wider range of circuitry.

LYDIA KAVRAKI | AGE 34

SOFTWARE

RICE UNIVERSITY

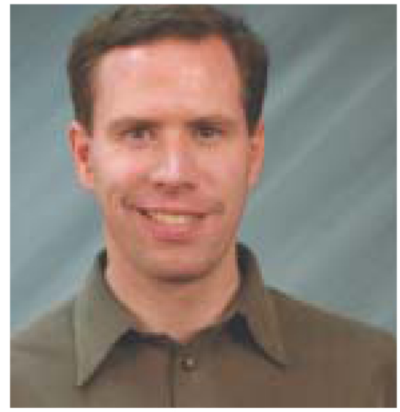
Lydia Kavraki made her first move between worlds when she left Greece to do a PhD in computer science at Stanford University. Drawn to the human potential of robotics, Kavraki studied how robots—from assembly line "arms" to autonomous machines—assess the obstacle-laden world and move around in it. She then created an algorithm that rapidly generates a path for a robot to follow through a given environment, using descriptions of how the robot moves, the space it's in, obstacles it must navigate and its beginning and end points. Today, most papers on robot-path planning cite her algorithm, and engineers in the automotive industry are using variations of it to build better robotic assembly lines. Kavraki, meanwhile, has moved to a new research world, applying the rules of her algorithm to predict how two molecules will move through space and interact with each other—crucial to designing drugs. Intense and determined, Kavraki finds the two problems closely linked: "There is a potential here for solving problems that could affect our lives, whether it's a robot that helps disabled people get out of bed or a tool that helps find a compound to treat disease."

KALANICK: DAVE LAURIDSEN

MATT KEYSER | AGE 32

ENERGY

NATIONAL RENEWABLE ENERGY LABORATORY



Matt Keyser revels in pedaling his bike amidst a pack of racers pounding down a precipitous mountain road. During sane moments, Keyser designs transportation technology at the National Renewable Energy Laboratory in Golden, CO. He's received two patents since 1992, with three more in the works. In 2001, Keyser and coworkers significantly extended the life span of lead-acid batteries in cars. Batteries provide a power surge to a vehicle's starter, then recharge. Normally, the process encourages sulfuric acid to oxidize, which ruins the negative battery plate. But Keyser changed how the battery charges, reducing chemical reactions and extending battery life up to 400 percent. "That means fewer batteries in the landfill," he says. Ford Motor is testing the battery in a prototype electric vehicle. In 1997, Keyser wrapped a standard catalytic converter with a vacuum insulator to keep it hot for hours. The retrofit eliminated 80 percent of the tailpipe emissions that a car produces while warming up. The unit is being commercially developed by auto parts supplier Benteler. Keyser particularly likes its adaptability: "You can put it on a new car, or a '78 Pontiac."

KARA KOCKELMAN | AGE 32

TRANSPORTATION

UNIVERSITY OF TEXAS AT AUSTIN

In Kara Kockelman's transportation models, there is no place to hide. The civil engineering professor crunches data on where people shop, work and go to school, what kinds of vehicles they buy, real-estate development trends and demographics to help devise optimal transportation policies. Her results are sometimes provocative: for example, from traffic data, she calculated that a large SUV slows traffic by spending as much time lumbering through an intersection as 1.41 passenger cars. Kockelman says, "We can't build our way out of congestion," and argues that road users should therefore shoulder the costs they impose on others. Her studies support, for example, the selective enactment of something called "credit-based congestion pricing": drivers would be allotted a certain number of commuting trips, which they could use or trade, the way power plants trade emissions credits. Such ideas are not particularly popular, but, Kockelman maintains, "I divorce myself from the emotions of the issue and allow the data to tell me what's happening." And Kockelman practices what her studies preach: she takes the bus to work.

J. JOSEPH KIM | AGE 32

MEDICINE

VIRAL GENOMIX

Viruses learned how to better infect people over millions of years of evolution; chemical engineer and MBA J. Joseph Kim is using their knowledge to fight other diseases. Kim figures to use the viruses' strategies as the basis for new drugs for cancer and inflammatory illnesses. In 2000, after several years at Merck, Kim founded Viral Genomix in Philadelphia, for which he has raised $1 million. "Since I was in high school I wanted to start my own biotech company," he says. His company may soon have its first drug: Kim has tinkered with a protein called vpr, which helps the HIV virus replicate, and has coaxed it to trigger cell death in more than 50 different cancer cell lines. So far, the protein has worked in laboratory cultures and in mice and macaques; Kim intends to begin testing it in human cancer patients within a year and a half. To that end, Viral Genomix has established a partnership with the University of Pennsylvania. Kim is also developing a drug based on vpr that can limit the proliferation of the immune system cells that cause rheumatoid arthritis and psoriasis.

REINER KRAFT | AGE 33

INTERNET AND WEB

IBM

The Internet is a great set of parts. Reiner Kraft wants to make them a more valuable whole. One way is to exploit the many computers linked to the Internet to solve massive computing tasks that no single computer could handle well. Kraft coinvented a program that parcels out such tasks over the Internet to thousands of PCs; each solves its morsel, and the program integrates the solutions. In 1998, IBM applied for a patent based on Kraft's distributed-computing scheme, which is used increasingly to crack computing problems. Kraft then created jCentral and xCentral—custom search engines for IBM's programmers. They search and return Java and XML programs, respectively—the software behind many Web applications—and nothing else. This allows the company's programmers (and non-IBMers, too) to much more efficiently build libraries of code for creating advanced applications that leverage the Internet's capabilities. Kraft has cranked out numerous other programs that integrate Internet functions and has filed 80 patent applications. Despite his prolific youth, however, Kraft frets about what's been left undone. "I worry," he says, "that I am missing some good opportunities."

TR100PROFILES

STEVEN LAKEN | AGE 30

MEDICINE

EXACT SCIENCES

Deadly genetic defects often involve single-nucleotide polymorphisms—single changes in the base pairs that make up DNA. As a graduate student at Johns Hopkins University, Steven Laken discovered that such a change occurs in six percent of Ashkenazi Jews and correlates with a 20 to 30 percent risk of colon cancer. With 20 million Ashkenazi Jews potentially at risk, Laken was not satisfied with simply finding the defect; he wanted to devise a rapid test for it. He created a lab procedure that separates DNA into fragments and then uses mass spectrometry to quickly search the fragments for the polymorphism. Doctors are now using the technique to screen patients with Ashkenazi backgrounds for colon cancer. After completing his graduate work, Laken joined Maynard, MA-based Exact Sciences, where he is now adapting the innovation for broader genetic tests, including one for nonpolyposis colon cancer, the most common inherited form of the disease. Laken believes his methods could spot virtually any illness with a genetic component, from asthma to heart disease.

PAUL KRAJEWSKI | AGE 33

TRANSPORTATION

GENERAL MOTORS

When he left the University of Michigan, Paul Krajewski was an expert in "creep" behavior related to all things aluminum. In the jargon of metallurgy, creep is heat- and stress-related deformation, and it's part of the reason aluminum is tricky to use for making cars. Aluminum is about 67 percent lighter than steel, but it is far more susceptible to cracking when deformed. Today Krajewski is a leading materials scientist at General Motors, devising ways to engineer aluminum so it can be used in mass production of lighter and more fuel-efficient family sedans and SUVs instead of just pricey handmade exotic cars. Krajewski invented a flash-heating technique that allows aluminum to bend on the assembly line without cracking. To ease one manufacturing process, he even developed a lubricant using milk of magnesia. Krajewski has won seven patents related to his techniques, which will help General Motors build cars with "creases and curves, anything that would excite the eyes of the customer," he says. And those lightweight parts should also excite customers when they get to the gas pump.

CHRISTINA LAMPE-ONNERUD | AGE 34

MATERIALS

TIAX

Christina Lampe-Onnerud's energy is boundless. She's a cellist, a master of jazz dance and has directed award-winning choruses. Boundless energy is also her technological goal. During doctoral work in inorganic chemistry in her native Sweden, Lampe-Onnerud patented a new cathode material that increased the power of lithium batteries. After leading research devising high-energy materials at two startups, she joined New Jersey-based Bell Communications Research in 1995. There she helped develop prototypes of the first lithium batteries made from thin-film polymers and the first practical process for manufacturing them. The batteries were smaller, more powerful and safer than conventional lithium batteries. Today the technology is licensed by many major battery makers. With seven more patents filed, Lampe-Onnerud now oversees 10 labs that investigate new battery materials for Tiax, which bought them from Cambridge, MA-based consulting firm Arthur D. Little. As a consultant, Lampe-Onnerud has led research teams at numerous companies. Her goal: "to cram as much power as possible into a battery without it blowing up."

CORINNA E. LATHAN | AGE 34

MEDICINE

ANTHROTRONIX

While involved in biomedical studies funded by NASA, Cori Lathan realized that astronauts in orbit encounter physical challenges much like those faced by people with disabilities. An astronaut, for example, must learn to move in an awkward space suit much the way a spinal-cord injury victim may have to relearn to walk. The experience guided Lathan in her search for better assistive tools as founder and CEO of College Park, MD-based AnthroTronix. An expert in human-performance engineering, Lathan devised interfaces that allow children to communicate with a half-meter-tall robot via body movements. Wireless sensors are placed on the child's body, and Lathan's playful, furry JesterBot solicits and mimics the movements and facial responses of its human buddy. The interaction can help a child with cerebral palsy get through painful physical therapy. Lathan is applying similar ideas to army research. Gestural interface technology can keep a night patrol leader in wordless contact with soldiers equipped with goggles that display his gestures as small icons. "I never thought about what I wanted to be," she says. "I always just looked for cool things to do."

LATHAN: MICHAEL VENTURA

RAYMOND LAU | AGE 30

SOFTWARE

IPHRASE TECHNOLOGIES

At 16, Raymond Lau wrote StuffIt, which soon became the prevailing software for compressing files on Macintosh computers so they take up less space. But Lau really heard his calling when he realized "the mathematical models for data compression are pretty similar to those for language processing." He joined MIT's Spoken Language Systems Group in 1994 and was central to its Galaxy project, producing software to recognize speech and interpret language, then deliver database information. He followed with Galaxy II—software that lets U.S. marines access information hands-free. Lau then used Galaxy II as the backbone of the MIT lab's most ambitious project: Mercury. The system allows anyone to call the lab, speak to a computer and book flights on 23 airlines, as if talking to a travel agent. In 1999 Lau became chief technology officer of startup iPhrase Technologies in Cambridge, MA, to apply his expertise to written words. IPhrase programs have advanced search capabilities for Web sites such as Yahoo! Finance and Schwab.

DER-HORNG LEE | AGE 34

TRANSPORTATION

NATIONAL UNIVERSITY OF SINGAPORE

Singapore leads the world in fighting traffic with technology. Vehicle sensors are ubiquitous, and so are message signs warning drivers of upcoming jams. Drivers are even charged higher tolls during rush hour. But when the island government seeks to boost the IQ of these "intelligent highways," it turns to Der-Horng Lee, a civil engineer at the National University of Singapore. He is in demand among transportation engineers and companies worldwide, helping them write better software that models traffic and controls road signals and signs in real time—for example, changing urban stoplight sequences on the fly as drivers flee rush-hour highways. Lee says traffic prediction is like weather prediction, only tougher. Predictions must be done quickly and account for the fact drivers might change plans after hearing them. The key is having the right algorithm, based on the right traffic simulation model. Most models assume group behavior, but Lee's "microscopic" models acknowledge that some traffic-bound drivers will sit in the mess while others will cut through city streets or choose a longer highway route.

KELVIN LEE | AGE 32

MEDICINE

CORNELL UNIVERSITY

Mad-cow disease occurs when an unruly protein called a prion causes healthy proteins in cattle brains to misfold. The same is true for the human versions of mad cow—"variant" Creutzfeldt-Jakob disease, which is contracted from beef, and the naturally occurring "sporadic" form. But until Kelvin Lee unleashed a new style of protein analysis, diagnosing these maladies required a postmortem brain biopsy—obviously, too late for patients. During postdoctoral work at Caltech in 1996, Lee identified a marker protein for sporadic Creutzfeldt-Jakob disease, yielding the first premortem test for the ailment. Lee went beyond the traditional method of studying a few proteins at a time; instead, he simultaneously analyzed the 2,000 proteins in human spinal fluid to pick out the telltale compound. In 1997 he confirmed that the disruptive protein also appears in mad-cow-afflicted cattle. People are now being tested for the protein in the U.S. and Europe. No one has confirmed whether the same marker characterizes variant Creutzfeldt-Jakob disease, but Lee's team recently identified other protein indicators that may prove fruitful. Lee is also working on a similar test for Alzheimer's.

ANDREAS LENDLEIN | AGE 32

MATERIALS

MNEMOSCIENCE

Most matter isn't very smart. But some exotic materials have memory: you can bend them, but when heated they return to their original shape. Engineers have tinkered with these materials for robotic and automotive applications, but polymer chemist Andreas Lendlein envisions their use in implantable therapeutic devices. In 1997, while working at MIT, Lendlein became the first to develop a biodegradable shape-memory polymer that responds to body temperature. A surgeon could insert a compressed polymer through a tiny incision; once inside the body it would expand. The payoff could be improved coronary stents to prop open blocked arteries, or scaffolds for growing new organs. A polymer with cells attached could be inserted to replace lost cartilage; triggered by the body's warmth, the polymer would expand into the shape of the missing cartilage, then degrade as new tissue grew. Lendlein returned to his native Germany and cofounded mnemoScience, in Aachen, to commercialize his technology. MnemoScience's researchers have successfully tested Lendlein's materials in animals, and they hope to release their first medical product in a few years.

TR100PROFILES

MAX LEVCHIN | AGE 26

INTERNET AND WEB

PAYPAL

After emigrating from Ukraine to Chicago as a teenager, Max Levchin enrolled as a computer science student at the University of Illinois so he could create and break codes. He moved to Silicon Valley after graduation to start a company based on his cryptography passion. In 1999, he cofounded PayPal in Palo Alto, CA, which quickly became the Internet's leading person-to-person payments processor. One in four transactions on eBay is settled using PayPal's system for debiting and crediting checking accounts and charge cards. In February, the company went public, raising $70 million. As chief technology officer, Levchin not only manages servers that store encrypted data about the company's 15 million members but has led the development of an antifraud program called Igor, named after a Russian fraudster it helped apprehend in 2000. Igor monitors PayPal's transactions for unusual behavior, alerting personnel to freeze suspicious accounts or head off cash en route to dubious destinations. The FBI has also enlisted Igor to combat wire fraud. Citibank and Bank One, and even eBay itself, have launched rival online payment services, but none has matched PayPal's market share.

MARIANGELA LISANTI | AGE 18

NANOTECHNOLOGY

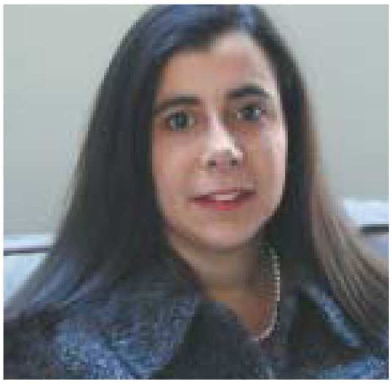
HARVARD UNIVERSITY

Unchallenged by high-school physics labs, Mariangela Lisanti went looking for a "real" project the summer after her junior year. She approached nanotechnology expert Mark Reed at Yale University. His challenge: design a better way to measure the conductance of a single atom in a nanowire. With virtually no help, Lisanti taught herself quantum mechanics, built an apparatus at Yale and generated data. Reed was floored: "In two months she did what often takes postdocs one or two years—with significantly less supervision." After her senior year, Lisanti improved her apparatus so it generated more data in a day than other approaches did in three months. She spent $35 on parts; other setups cost $100,000. Reed says Lisanti also unveiled aspects of conductance "never observed before." Researchers nationwide have asked to use her technique. The first student to place first in the Intel Science Talent Search and the Siemens Westinghouse Science and Technology Competition, Lisanti is now a freshman at Harvard University. "My passion," she says with a joyous smile, "is to explain things that haven't been explained."

PAMELA LIPSON | AGE 34

SOFTWARE

IMAGEN



In 1997, after finishing her PhD and starting up Imagen in Cambridge, MA, Pamela Lipson would get phone calls from her mentor, Alex d'Arbeloff, chairman of the MIT Corporation. "Focus," he'd always tell her. Lipson had devised algorithms that could rapidly identify and classify digital images. Venture capitalists wanted them, but for far-flung applications: to improve Web searches for images, or for face recognition, video-database indexing or pharmaceutical R&D. But it was not clear any of these emerging markets would embrace Lipson's technology. In a quest for real customers, Lipson bet on inspection of printed circuit boards. She adapted Imagen's software so it could identify production errors from a digital snapshot without misidentifying normal variations in parts. She designed a straightforward interface so users could easily modify the software. Inspections using Imagen software enhanced productivity without introducing lag. "What used to take five minutes now takes 20 seconds," says Paul Keating at Teradyne, which has rights to use Lipson's technology. Now that's focus.

JEFFREY LONG | AGE 32

NANOTECHNOLOGY

UNIVERSITY OF CALIFORNIA, BERKELEY

Chemist Jeffrey Long is daring to remake the ubiquitous computer hard drive. Long is devising ways in which chemists can assemble large inorganic molecules packed with different metals to create a host of novel materials for use in the emerging field of nanotechnology. His first target is the molecular magnet, a chemical structure whose electrons can be set spinning in synchrony by a magnetic field. Molecular magnets are a potential replacement for the increasingly crowded metallic films that constitute computer hard drives. Each molecular magnet could represent one bit of memory, enabling storage densities a thousand times greater than those of the best existing films. Long began building his own molecular magnets in 1997, demonstrating a scheme for packing them with progressively more chromium, cobalt and nickel. Unfortunately, his best clusters can only be magnetized at a chilly -270 °C, just 3 °C above absolute zero. Making more practical molecular magnets may take years, but if this field heats up, it could revolutionize computer storage.

IHOR LYS | AGE 32

HARDWARE

COLOR KINETICS

Ihor Lys wants to color your world with light that morphs, fades and blends in computerized patterns, thanks to multihued arrays of light-emitting diodes (LEDs). Lys came to lighting after 11 years at Carnegie Mellon University, where he studied electrical engineering and robotics. While working on an LED-based display for a robot, he realized that by combining bright blue LEDs—just then being reported in labs—with existing red and green ones, he could create new possibilities for digitally controlled illumination. But it took circuit design virtuosity to produce lush visual environments using these simple indicator lights. In 1997 he teamed up with engineer George Mueller and launched Boston-based Color Kinetics, which reported revenues of $17 million in 2001. Colors from its LED fixtures fill corporate lobbies, swimming pools, spas—and even emanate from the cables of Philadelphia's Ben Franklin Bridge. Lys "keeps pulling off miracles," says the MIT Media Lab's Michael Hawley, a Color Kinetics board member. But Lys views his mission in simple terms: "I see things that are expensive and difficult, and I want to make them cheap and easy."

SURYA MALLAPRAGADA | AGE 29

MEDICINE

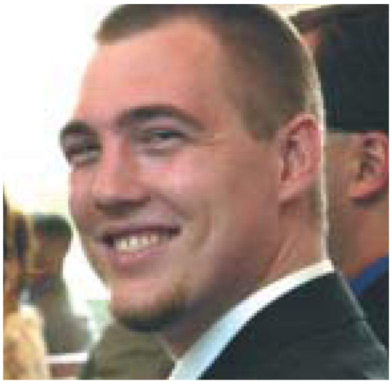
IOWA STATE UNIVERSITY

If laboratories are ever to become factories that can produce human organs, scientists must find ways to grow cells faster and in a more controllable way. A chemical engineer who trained at the intensively competitive Indian Institute of Technology, Bombay, Surya Mallapragada is closing in on that goal. Mallapragada has designed biodegradable polymer scaffolding to guide the growth of individual cells in the same way that wooden supports guide the tendrils of a grapevine. In experiments, she implanted her scaffolds in rats, tied the ends of torn nerve cells to them and showed that the cells could relink by growing along fine grooves on the polymer surface. Carving the grooves was key; the usual technique of bombarding the scaffold with ions degrades the polymer, so Mallapragada used alternatives like laser etching and atomic-force microscopy that minimize degradation. To entice tissue to grow quickly, Mallapragada lined the grooves with special cells that ooze growth-inducing proteins. When she's not busy teaching nerve cells to grow, Mallapragada spends a little time learning tae kwon do.

ROB MALDA | AGE 25

INTERNET AND WEB

SLASHDOT



While Rob—don't call him Robert—Malda may fit the irreverent hacker stereotype, his finest hack does not. Malda is founder of Holland, MI-based Slashdot, a Web site cum online community cum Internet Zeitgeist-meter visited by more than 250,000 surfers daily. What started in 1997 as an online hang-out for Malda's cronies to trade banter on geek subjects is now "the number one site for tech news and geek ranting," according to the *Washington Post*. Contributors recommend news items to Slashdot, where Malda and his small staff create links to the stories and write introductory paragraphs. Readers post comments, which are then graded by other readers. Many times, Web sites whose addresses are cited experience the "Slashdot effect"—an increase in traffic so sharp that their operations sometimes halt. The open-source program that runs Slashdot, which Malda created and regularly works on, is intuitive enough to have attracted 500,000 registered users. Countless others have downloaded it to run their own online discussion groups. As Malda continues to refine the Slashdot experience, he will refine the way the world experiences the Internet.

SCOTT MANALIS | AGE 29

NANOTECHNOLOGY

MIT

One of the first things you notice about Scott Manalis's CV is a substantial list of patents. A tour of his orderly but jam-packed lab, replete with an ultrasensitive micro-accelerometer and microelectromechanical devices, confirms that Manalis likes to build gadgets that work on the scale of nanometers and micrometers. Trained in applied physics, and an expert on the equipment used to image and manipulate atoms, he hopes to create revolutionary new tools for advancing molecular biology. He wants to get direct information on DNA or protein molecules by binding them to, say, silicon transistors or tiny cantilevers. His dream, he says, is that within five to 15 years, he'll be able to "stick a probe into a cell, connect it to a computer" and get real-time information on the cell's proteins and genes. Such a tool would be invaluable to molecular biologists, replacing weeks or months of laboratory analysis. It may take a while, but Manalis is already creating the technology to make his dream reality.

MANALIS: WEBB CHAPPELL

TR100PROFILES

LARRY MIANZO | AGE 34

TRANSPORTATION

VISTEON

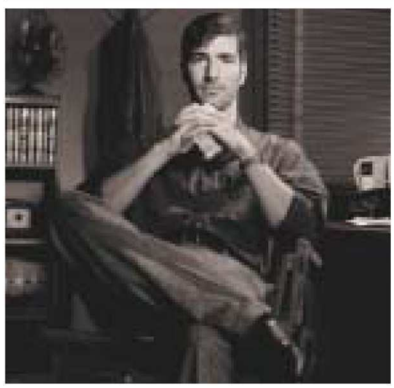
Few people consider the internal-combustion engine environmentally friendly. Larry Mianzo could help change that. Mianzo is a key player in the auto industry's efforts to build cleaner, more efficient engines. His innovations could usher in something called "electromagnetic variable valve timing." In an automobile engine, valves are opened and closed in a fixed pattern by rotating camshafts. Eliminating the cams and moving each valve with an electromagnetic actuator allows optimal control of valve timing, ending power losses and providing a more tightly controlled combustion temperature. The result: a 15 to 25 percent boost in fuel economy and dramatically lower emissions. Mianzo has been working on automobile controls for the past eight years—first for Ford Motor, now for its spinoff Visteon, in Dearborn, MI. He has 12 patents issued or pending, including one on a novel road simulation strategy for testing new vehicles that has helped save Ford Motor $1 million a year. Mianzo has accomplished all this while earning a PhD and hasn't missed a day of work since 1992.

STEVE McCANNE | AGE 33

INTERNET AND WEB

INKTOMI

Steve McCanne's career as a rock star fizzled in high school. But noodling on a synthesizer did spark his interest in digital signal processing, which blossomed into graduate work at Berkeley National Laboratory. There he helped his mentor, Van Jacobson, invent the "Internet multicast backbone" (Mbone), which led to Internet standards for streaming media and enables people at scattered locations to collaborate using video, audio and a whiteboard. Among Mbone's first users: NASA engineers. In 1998, McCanne cofounded FastForward Networks and pioneered the first scalable techniques for live Internet broadcasting. In 2000 Internet giant Inktomi bought FastForward for $1.3 billion to get its multimedia tools—and McCanne, now chief technology officer. Inktomi, in Foster City, CA, performs cataloguing and searching for huge portals like America Online and MSN. McCanne is now devising systems to let big businesses, including Ford Motor, McDonald's and Merrill Lynch use video webcasting throughout their own networks. Someday he'd like to write a book about "how the Internet really works."



LOU MONTULLI | AGE 32

INTERNET AND WEB

FREELANCER

It's one thing to devise a key innovation for the Internet. Lou Montulli has designed half a dozen. While a computer science major at the University of Kansas in 1991, he wrote Lynx, a program that enabled a computer user to automatically link text documents. It became one of the earliest and most popular World Wide Web browsers. At the same time, Montulli was a leading figure in the grass-roots effort to improve several fundamental computer languages and protocols, including the hypertext transfer protocol—the addressing scheme that links Web pages—and HTML, the language for creating text and images on Web pages. In 1994 he moved to California to work as a founding engineer at what became Netscape, developing the first commercial Web application. Not all of his innovations have been universally embraced: he is responsible for cookies—data files that enable Web sites to recognize returning users—as well as blink tags—those endlessly flashing words on Web pages. Shrugging off the burden of being named *People* magazine's sexiest Internet mogul of 1999, the freelancing Montulli continues to experiment with new ways to exploit the Internet.

SEAN J. MORRISON | AGE 33

MEDICINE

UNIVERSITY OF MICHIGAN

Stem cells have become icons of medical hope, and Sean J. Morrison has made fundamental discoveries that explain their workings. As a postdoc at Caltech, Morrison devised a way to harvest neural stem cells from fresh tissue rather than from tissue cultured in the lab, where stem cells might have been created as an artifact of the culturing process. In so doing, Morrison clarified many of the cells' properties. "He is one of the most talented stem cell researchers," says David J. Anderson, Morrison's advisor at Caltech. While studying similarities between stem cells and cancer cells, Morrison and a collaborator made the surprising discovery that tumor growth may be driven by rare "cancer stem cells." Now an assistant professor at the University of Michigan, Morrison recently cofounded Cancer Stem Cell Genomics to investigate the possibility that that discovery could lead to better ways of developing cancer-killing drugs. The nascent company is Morrison's second business foray. In college he developed an inexpensive process for mass-producing fungi, but his company lacked capital. Given stem cells' medical applications, his new business is not likely to have similar trouble.

MONTULLI: MICHAEL GRECCO/ICON

CHAHAB NASTAR | AGE 33

SOFTWARE

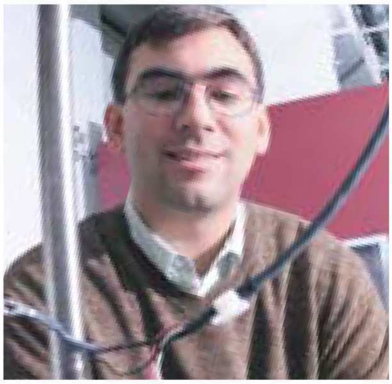
LTU TECHNOLOGIES

Chahab Nastar has always had a passion for patterns, whether he was tracking the popularity of his rock band Busy Being Born or designing software to distinguish unhealthy heart motions, which he did as a researcher at the University of Paris. Now he's pouring that passion into helping computers understand everyday objects and scenes—a challenge that's still "extremely difficult, if not impossible, for machines," he says. Show a picture of your beach vacation to today's average image-recognition program, and it can find similar beach scenes. But it can't tell which beach is pictured or who is sunbathing. To move to that level, Nastar's Paris-based startup, LookThatUp—now LTU Technologies—has enhanced image-recognition techniques with artificial-intelligence-based learning algorithms. Now, the more images of, say, cars and animals LTU's system memorizes, the more quickly it can classify a Volkswagen or zebra. The system's industry-leading recognition speed, a mere 200 milliseconds per image, has helped LTU sell software licenses to a dozen U.S. and European companies.

MILAN MRKSICH | AGE 33

MATERIALS

UNIVERSITY OF CHICAGO



Marrying biological and electronic systems could yield advances in drug discovery, bioweapon detection—even computing. But the chemistry must be just right for living cells and electronics to talk. Milan Mrksich is the perfect matchmaker. The University of Chicago chemist coats the surfaces of electronic devices with organic molecules that can convert a chemical signal into an electrical one, and vice versa—creating a means of communication unlike anything developed by the handful of other researchers working on hybrid devices. Cells in a bioweapon detector, for example, could produce an enzyme when infected by a virus. The enzyme would interact with molecules on the surface of a microchip, triggering an electrical signal that would set off an alarm. With funding from the U.S. Department of Defense, Mrksich aims to build a prototype detector within five years. He also envisions computing devices that would exploit the different ways living and electronic systems handle information. But for now, Mrksich is just excited that he's sparked a conversation between cells and circuits.

BILL NGUYEN | AGE 30

TELECOMMUNICATIONS

SEVEN NETWORKS

Bill Nguyen is a serial entrepreneur. He led business or technical development in four startups before founding Onebox.com, a company that was among the first to provide e-mail, voice mail and fax access in a single mailbox over a conventional phone. Nguyen sold Onebox for $850 million in 2000, but not before hearing from wireless subscribers that they lacked similar data retrieval services. His solution? Seven Networks. Software from the Redwood City, CA, company lets customers of a wireless carrier access e-mail, voice mail and other Internet services simply by calling the carrier. Unlike subscribers to other wireless services, Seven customers don't have to install extra hardware or software. So far, Cingular, Sprint PCS and Britain's mmO2 have implemented Seven's innovation, and Nguyen has secured $64 million in venture funding. His company has also partnered with Microsoft to create software that allows a company's employees to wirelessly tap into its intranet. How does Nguyen do it all? For one thing, he is notorious for sleeping only three hours a day.

STEPHEN O'CONNOR | AGE 32

BIOTECHNOLOGY

NANOSTREAM

Stephen O'Connor is equal parts scientist, engineer and salesman. Armed with a PhD in chemistry from Caltech and more than a dozen jointly held patents, he helped start four companies, raising most of the seed money himself. His first venture made ultrafast optical sensors. His second, Clinical Microsensors, made DNA detection instruments he designed to quickly read the genetic makeup of plant and animal tissue; Motorola bought the company for $300 million. Money and experience gave O'Connor the confidence to found Nanostream in Pasadena, CA, in 1999. It makes custom chips that analyze microscopic amounts of blood or other fluids, some of the first commercial products in the rapidly growing field of microfluidics. With $11 million in funding, Nanostream markets the chips to pharmaceutical companies for drug discovery tests. Also in 1999, O'Connor founded CO2, a profitable incubator company that has invested in 11 local scientific startups by outfitting their labs. O'Connor's Caltech advisor, John Baldeschwieler, says his ex-student is "playing an increasingly important role in the economic development of Pasadena."

KAZUHO OKU | AGE 24

INTERNET AND WEB

ILINX

Commuters in Japan are staring into their hands—and Kazuho Oku is to blame. Oku used personal digital assistants in high school but only experienced the Internet when he enrolled at the University of Tokyo as a geology major. He was struck by how much more useful the Internet could be—especially to idle commuters on subways and trains—if it were easily accessible over handheld devices. He was soon spending his time in the university's computer department, devising a way to compress Web pages and developing software to convert them into a format for handhelds. The result was Palmscape, one of the world's first Web browsers for handhelds. Oku distributed Palmscape—intended for the Palm Pilot's Palm operating system—free over the Internet. Before finishing his studies, Oku was lured to Ilinx, a software company in Tokyo, where he developed his successor product, Xiino. It comes installed in a wide range of handhelds and is a leading browser for Palm products in North America, Europe and Japan. Oku is now adding capabilities that allow corporate clients and individuals to write their own custom applications.

LARRY PAGE | AGE 29

INTERNET AND WEB

GOOGLE

Google combs more Web pages, faster, than any other search engine. But perhaps just as impressive is that despite the dot-com meltdown, the company has never veered from its mission. Competitors have tried to reposition themselves as all-purpose "portals," only to slip from the radar screen. That thrills Google cofounder Larry Page, a feisty roller hockey player. Google has continued to expand the kinds of data it searches, recently adding Usenet news groups and retail catalogues. And it keeps expanding its tool set: for instance, Google now serves its results to cell phones. Copresidents Page and Sergey Brin *(p. 69)* have worked as equal teammates since they first devised their unique search software and went live in 1998. They are both competitive but know how productive they are working together. Their responsibilities often overlap, and they still share an office. For them, Google is about solving intellectual problems. Indeed, they recently recruited Novell and Sun veteran Eric Schmidt as CEO to manage their 300-plus employees, so they can continue to focus on technology. "Our goal is to keep innovating," Page says.

ALEXANDER OLEK | AGE 32

BIOTECHNOLOGY

EPIGENOMICS

Soon after Watson and Crick found that DNA is made up of four subunits, including one called cytosine, scientists discovered a so-called fifth subunit: methylated cytosine. Experiments in the 1990s showed that methylated cytosine acts as a switch that can turn a gene on or off. But researchers had trouble distinguishing it from ordinary cytosine. Alexander Olek found an easy way to make it stand out, exposing relationships between the switch and disease. Olek also developed lab techniques for quickly scouring large volumes of DNA for the switch. His work made him a pioneer in "epigenetics," which explores how environmental factors alter DNA. Olek, who dreams of helicoptering to a mountaintop to ski virgin snow, brings an adventuresome attitude to his work. At 19 he started his first enterprise, which looked for genetic features of diseases common in South America. While he was finishing his doctorate, Olek started Epigenomics in Berlin to advance his methylation work. With $35 million of investment capital, Epigenomics plans to market cancer detection tests that sense tumors' methylation signals.

VIJAY PANDE | AGE 31

BIOTECHNOLOGY

STANFORD UNIVERSITY

If scientists understood how the body's proteins folded, they could better battle diseases like Alzheimer's. But analyzing a protein's trillions of possible folding steps is daunting, even for a supercomputer. In 1999 Vijay Pande, a professor of chemistry and structural biology at Stanford University, wrote algorithms that enable thousands of isolated computers to calculate tiny portions of a folding sequence and combine their solutions. The pragmatic Pande then sought advice from distributed-computing entrepreneur Adam Beberg (a former TR100 honoree) on how to integrate his code into a screen saver that PC users could download. Dubbed "Folding@home," the software makes calculations any time the PC's screen saver is running and reports the results to Pande's computer. Since the project's October 2000 debut, some 75,000 volunteers worldwide have helped simulate, for the first time, the complete folding behavior of five important proteins. Born in Trinidad to Indian parents, Pande is now using distributed computing to map the final folded structures of the proteins. On any given day, 35,000 PCs are providing the computing power.

SUZIE HWANG PUN | AGE 27

MEDICINE

INSERT THERAPEUTICS

Think of Suzie Hwang Pun as a traffic cop for genes. The chemical engineer uses polymers to carry injected genes through the bloodstream. With a system of molecular tags, she can direct a gene—say, one that blocks cancer progression—to just the right spot—like the nuclei of cells in a tumor. It's a trick that could solve a huge problem in gene therapy research: a new gene does no good if it doesn't make it to the right place. While viruses are the typical delivery vehicles in gene therapy, they're hard to manufacture and can be intercepted by the immune system. Pun's materials avoid those problems and open the possibility of delivering drugs, as well as genes, with exquisite precision. "This is the tip of the iceberg," says Caltech chemical engineer Mark Davis. He was so excited by Pun's accomplishments as a graduate student in his lab that he founded Insert Therapeutics in Pasadena, CA, primarily to commercialize her work. The clear-spoken Pun jumped at the chance to be a senior scientist and employee number one. If all goes well, her technology could enter human trials within a few years.

JOSEPH REAGLE | AGE 29

INTERNET AND WEB

WORLD WIDE WEB CONSORTIUM

Joseph Reagle bikes rather than use polluting transportation. He eats vegetarian so animals are not killed, and brings a quiet but strong sense of social conscience to bear on issues like trust, privacy and intellectual-property rights on the World Wide Web. After earning his graduate degree from MIT's Technology and Policy Program in 1996, Reagle established himself as a creative thinker at the World Wide Web Consortium, based at MIT. He has driven several initiatives that will dramatically affect online interactions. He led the group that developed a standard way for Web sites to disclose their privacy policies, telling people what might be done with personal information. He coordinated input from far-flung institutions to create rules recognizable by all Web browsers for signing online documents, so people can leave unique stamps verifying that documents have been made or approved by them. Sound like fun? It was for Reagle, who says innovation is not just for technology but for culture. Web inventor Tim Berners-Lee, who oversees the consortium, says Reagle is "continually" looking to better the relationship of the Web to society.

STEPHEN QUAKE | AGE 32

MATERIALS

CALTECH

The biotech industry dreams of automating millions of biological experiments on mass-produced chips. Colleagues say Steve Quake has the creativity, intellect and ambition to make it happen. When Quake was a Stanford University postdoc, he investigated the behavior of biological polymers. After becoming a Caltech professor he developed his first microfabricated tools, which use electric fields to sort cells and manipulate DNA molecules. Soon thereafter, Quake used soft lithography to build the first set of microvalves and pumps practical enough to be mass-produced, a key step toward developing the hotly anticipated chips. In 1999, Quake and some former college buddies founded San Francisco-based Fluidigm to supply his patented equipment and intellectual property to life science and pharmaceutical companies. Fluidigm has received $50 million in capital and recently signed a deal to supply GlaxoSmithKline. Now a tenured professor, Quake divides his time between researching the structure and function of proteins and devising more-sophisticated microfluidic tools.

RAJESH REDDY | AGE 31

TELECOMMUNICATIONS

JULY SYSTEMS

In Bangalore, India, six years ago, programmers working for overseas firms were commonplace. Innovative startups were not. That changed after Rajesh Reddy, trained at the Bangalore Institute of Technology, founded Gray Cell Technologies in 1996. Reddy ambushed a Motorola vice president on business in Bangalore and showed him that Gray Cell's desktop-to-wireless network was more advanced than similar Motorola technology. Motorola soon licensed Gray Cell's application for sending e-mail via cell phones and pagers and became Reddy's first corporate customer. More U.S. investment in Indian information technology companies followed. By 1999 Reddy had renamed his company Unimobile and moved it to Silicon Valley, where it operated a wireless network connecting 370 carriers in 130 countries. The dot-com bust crippled the company, though. By summer 2001 Reddy was back in Bangalore launching July Systems, to create software that integrates wireless networks and devices into a global superstructure. With the backing of investor Ashok Narasimhan, and with business lessons learned, Reddy is confident July Systems will become a significant player this summer.

TR100PROFILES

VINCENT RIJMEN | AGE 31

SOFTWARE

CRYPTOMATHIC

Rules "get in the way most of the time," says cryptographer Vincent Rijmen. Last year the U.S. government chose the Belgian citizen's encryption algorithm, Rijndael (pronounced rain-doll), as its new Advanced Encryption Standard. Rijndael replaced the aging, no longer unbreakable Data Encryption Standard, used since 1977 by U.S. government agencies and companies to safeguard everything from e-mail to phone calls. It beat submissions from many large competitors, including IBM, and will be widely used. Rijmen created Rijndael with Joan Daemen, 36, a fellow postdoc at Katholieke Universiteit Leuven in Belgium. The duo pulled off the upset in part by throwing away what Rijmen calls a cryptography "rule": to be secure, an encryption algorithm has to be exceedingly complex. Advanced computers would need trillions of years to decrypt information encrypted using Rijndael—yet the algorithm can run on devices like smart cards. Already, manufacturers plan to include Rijndael in cell phones, credit cards and Web browsers. "People will be using it without ever knowing," says Rijmen, who recently became chief cryptographer at Cryptomathic, an Aarhus, Denmark, security firm.

DAVID SABATINI | AGE 33

BIOTECHNOLOGY

WHITEHEAD INSTITUTE FOR BIOMEDICAL RESEARCH

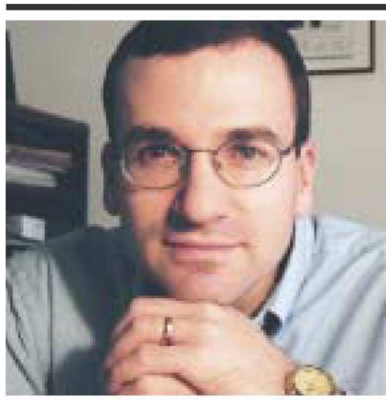
"Right now we have no way of saying, 'Give me a drug candidate, then give me a list of every protein in the human body it interacts with,'" says David Sabatini, whose mellow demeanor is more characteristic of a jazz guitarist than a molecular biologist. "But my technology can do that." The payoff, he says, could be better drug design. His technology is a glass chip, essentially a microscope slide, spotted with several thousand mammalian cells. Each spot of cells makes a different protein; researchers can wash a potential drug over the slide to see how it interacts with thousands of proteins at once. In the past, testing all those proteins might have taken months. Today a patent on the chip is pending, and Sabatini has raked in $6.5 million in capital for his Cambridge, MA, startup, Akceli. But drug screening is only one application: Sabatini aims to make a cell-based chip that will allow researchers to study every protein encoded in the human genome at once. He says his chip could allow researchers to identify the mutated genes that lead to disease.

JONATHAN ROSENBERG | AGE 29

TELECOMMUNICATIONS

DYNAMICSOFT

Thanks to Jonathan Rosenberg, the Internet could usurp the role of the old-fashioned phone network. The key is a set of computer instructions that make it practical for the Internet to carry not just data but two-way telephone calls, teleconferences and pages. This "session initiation protocol" also supports newfangled connections like instant messaging and "presence," which tracks who is available online at any given moment. Rosenberg produced the protocol with Columbia University telecom expert Henning Schulzrinne while working toward his doctorate at Columbia and overseeing video compression research at Bell Labs. The telecom industry heralded the protocol, and the Third-Generation Partnership Project, a high-profile colloquium for setting wireless standards, adopted it in 2000. As chief scientist at East Hanover, NJ, startup dynamicsoft, Rosenberg has since been cooking up a suite of related software that would enable wireless phones to download voice, text *and* video and would let company Web sites provide voice links to live customer service representatives.



JOHN SANTINI | AGE 29

MEDICINE

MICROCHIPS

John Santini knows all about managing chronic illnesses; he was diagnosed with lupus at age 12 and has been taking daily medication since. Small wonder he chose to pursue drug delivery technology. Today Santini is chief scientific officer of MicroChips, which he cofounded in 1999 to make pills and injections obsolete. The Cambridge, MA, company is developing an implantable chip that stores drugs and releases them at a programmed rate. Santini devised the technology as an MIT grad student. A dime-sized, surgically replaceable chip can hold several hundred single-dose drug reservoirs. Patients could control the chip's microprocessor remotely—a benefit for, say, patients taking pain medications. MicroChips recently began testing the chip with an undisclosed drug. Santini's technology could be ideal for delivering new protein drugs. Most proteins must be injected into the bloodstream because they are too fragile to survive the digestive system. But an implanted chip could replace such injections. And with the sequencing of the human genome, Santini says, "There's going to be an explosion in protein compounds in the next five to 10 years."

DAVID SCHAFFER | AGE 31

MEDICINE

UNIVERSITY OF CALIFORNIA, BERKELEY

David Schaffer spends most of his time making things grow: in his garden, orchids; in his lab, stem cells. The biomedical engineer is trying to coax stem cells that lie nearly dormant in the brain to multiply at a much quicker rate than they ordinarily do, which could help regenerate damaged nerve tissue in patients with Alzheimer's or Parkinson's diseases. Last year Schaffer and his colleagues discovered a protein that causes stem cells to grow, and he showed that the protein's action could trigger the repair of nerve cells in mice. By determining how the protein works, Schaffer may be able to get neural stem cells in human patients to replace damaged neurons. To carry the protein to stem cells, Schaffer is using inactivated viruses as delivery vans and is now tinkering with their molecular properties to help them find their targets precisely. Schaffer's background equipped him well for his work: he grew up in a family of doctors, was interested in mathematics and majored in engineering. Prodding stem cells to grow is harder than cultivating orchids, but the potential rewards are richer, too.

KEITH SCHWAB | AGE 33

NANOTECHNOLOGY

NATIONAL SECURITY AGENCY

Expect big things from Keith Schwab. Just don't expect to hear much about them. Schwab has advanced quantum physics with two seminal discoveries: At the University of California, Berkeley, he devised ways to exploit the quirky quantum behavior of a frictionless fluid called superfluid, which could lead to a superaccurate gyroscope, important for space navigation and to measure minute changes in the earth's rotation. Then, at Caltech, he became the first to measure the fundamental unit of heat flow, a constant that will limit nanoscale devices. That discovery was the subject of filmmaker Toni Sherwood's 2000 documentary *The Uncertainty Principle*, popular at film festivals. Schwab lowered his profile when he joined the tight-lipped National Security Agency's quantum computing initiative in College Park, MD. Its goal: a quantum computer, which could have unparalleled code-breaking power. Schwab is also building nanoscale machines to demonstrate another of physics' bizarre properties: superposition, a particle's ability to exist in two places at once. Schwab's work is unclassified—for now.

JAN HENDRIK SCHÖN | AGE 31

NANOTECHNOLOGY

LUCENT TECHNOLOGIES' BELL LABS

Hendrik Schön is reinventing the transistor at the place it was born. He and his Bell Labs coworkers have produced single-molecule transistors whose electrical performance is comparable to that of today's best silicon devices but which are hundreds of times smaller. Making such molecular transistors, which could lead to ultrafast, ultrasmall computers, has been a goal of researchers for years; Schön's clever design established Bell Labs as a leader in the race. But Schön is not interested in simply reinventing the transistor. He wants to change the very materials that form microelectronics, replacing inorganic semiconductors with organic molecules. Schön has made an organic high-temperature superconductor, renewing hopes that superconductors could have widespread electronic applications. He also helped devise the first electrically driven organic laser, which could mean cheaper optoelectronic devices. The soft-spoken Schön recalls being "very surprised" by how well his molecular transistors worked. But it won't be a surprise if Schön helps transform microelectronics.

KEVIN SHAKESHEFF | AGE 32

MATERIALS

UNIVERSITY OF NOTTINGHAM

The human immune system defends against foreign objects with vigilance, but Kevin Shakesheff wants to create lasting peace between synthetic surfaces and the biological world. He is building polymer scaffolds, on which living cells can grow, to form the backbones of what will one day be transplant-ready organs, as well as drug delivery vehicles that can steer themselves to target sites. That work began when the pharmaceutical sciences graduate spent a year in the lab of MIT bioengineering pioneer Robert Langer. He returned to the University of Nottingham in his native England to start his own lab. There, Shakesheff figured out how to incorporate stem cells as well as support cells that he calls the "unsung heroes" of tissue regeneration into biodegradable polymer structures for organs. Shakesheff is now using the technique to develop small polymer capsules that can deliver human cells to injury sites. Last year, the hard-working Shakesheff founded Regentec in Nottingham to commercialize his work. He's forging agreements with pharmaceutical companies to mass-produce miniature tissue and organ samples for drug testing.

TOM HYONGSOK SOH | AGE 32

TELECOMMUNICATIONS

AGERE SYSTEMS

When Tom Soh was a Stanford University graduate student, his focus was scholarly: to push the envelope in nanotechnology research. Things have changed since he arrived at Lucent Technologies' Bell Labs. Soh heads optical microelectromechanical development at Lucent spinoff Agere Systems, in Allentown, PA. His task is to make optical communications systems more efficient and intelligent. His group's first success was a microelectromechanical switching device that routes fiber-optic signals without converting them to electronic form and then back to optical. Those conversions cause the biggest bottlenecks in today's telecom systems, and Soh's optical switch offers huge gains in speed and capacity. Agere began large-scale production in March 2002, after it received significant orders from top customers. Soh has since led development of another product, the optical add/drop multiplexer, which allows light-wave transmissions to be added or dropped at critical nodes without electronic conversion. Currently overseeing 12 engineers, Soh believes great things can be achieved with team chemistry.

STEVEN SHAW | AGE 28

ENERGY

MONTANA STATE UNIVERSITY

Inside an airliner, vibration frays a tiny piece of insulation, exposing an electrical wire; an arc of electricity ignites vaporized fuel—and a disaster. That's what investigators suspect caused the 1996 explosion of TWA Flight 800. Electrical engineer Steven Shaw wants to make sure it doesn't happen again. While pursuing his PhD, Shaw wrote algorithms that allow sensors to interpret minute fluctuations along every electrical line in an aircraft or building. This information can help building managers find faulty equipment or wiring and help airplane inspectors pinpoint electrical malfunctions—before problems turn deadly. Now a professor at Montana State University, Shaw is equally adept at theorizing, coding and working in the machine shop. The California Energy Commission is testing Shaw's advanced load-monitoring systems on several state buildings. Better information about electrical flow can help building managers decide when to fire up backup batteries, fuel cells or expensive gas turbines.

ANNA STEFANOPOULOU | AGE 33

TRANSPORTATION

UNIVERSITY OF MICHIGAN

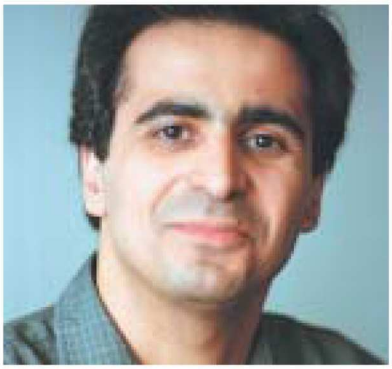
"The most interesting thing in the world," says University of Michigan professor and dirt biker Anna Stefanopoulou, "is balancing trade-offs to control complex systems." Stefanopoulou works on electronic valves that could boost the fuel economy of conventional car engines by an estimated10 percent and make practical exotic designs that are 30 percent more fuel efficient and free of nitrogen oxide emissions. A conventional engine regulates power with a throttle that controls airflow into cylinders; the timing of valves stays mechanically fixed. But the timing of electronic valves can vary infinitely, allowing the engine to "gain torque so fast it can break the crankshaft," Stefanopoulou says. The native of Greece is developing such controls using sophisticated mathematical modeling, while high-end car companies "rely more on intuition," says her Michigan colleague Jessy Grizzle. Stefanopoulou is also devising automated gears that would use engine compression to brake vehicles. She was already modeling the control of cars powered by fuel cells when the Bush administration dismantled an initiative to develop hybrid gasoline-electric vehicles—in favor of fuel cell power.

LISA SU | AGE 32

HARDWARE

IBM

People often ask Lisa Su why she works for IBM—after all, aren't startups where the glamour is? Su's response: "I can run a group that's like a startup, yet I have the resources available at IBM." Her Emerging Products group focuses on low-power and broadband semiconductors as well as biochips. Its first product is a microprocessor that improves battery life in handheld assistants and cell phones. Su hired the group's 10 employees and says their role is to develop broadband products that will "give my mom instant, unlimited access to information, anytime, anywhere, in any form." After joining IBM in 1995, Su, who has a PhD in electrical engineering, played a critical role in integrating copper connections into semiconductor chips, solving the problem of preventing copper impurities from contaminating the devices during production. The technology, unveiled in 1998, led to chips that were 10 to 20 percent faster than those with conventional aluminum connections. Su showed she had management acumen and was allowed to start Emerging Products. "Lisa became an IBM executive in five years," says colleague Scottie Ginn, "quicker than anyone I've ever seen."



VAHID TAROKH | AGE 34

TELECOMMUNICATIONS

MIT

Iran native Vahid Tarokh works so quickly that by the time people apply his advances, he is often on to something else. Such is the case with his breakthrough codes to improve the speed, capacity and clarity of wireless voice and data communications. He developed the codes in 1996 at AT&T Labs, yet U.S. and international telecom standards bodies didn't adopt them until 1999. Tarokh's codes solved the problem of how best to get a signal from a base station to a cellular phone without fading. Solutions proposed by others, such as adding an extra antenna to the phone or sending the same signal on different frequencies, weren't practical, so he created algorithms whereby multiple antennas at the base station could send the same signal simultaneously on the same frequency. For two months Tarokh worked day and night handcrafting his solution on huge sheets of paper. He moved to MIT in 2000 to work on "orthogonal frequency division multiplexing," an advanced scheme for wideband wireless communications. This summer Tarokh joins Harvard University as an electrical engineering professor.

VIVEK SUBRAMANIAN | AGE 30

MATERIALS

UNIVERSITY OF CALIFORNIA, BERKELEY

Vivek Subramanian is an inventor's inventor. His credits include a novel memory chip that led him to start Santa Clara, CA-based Matrix Semiconductor; a tiny, award-winning transistor; and his current project, ultracheap, flexible displays for note-taking gadgets. But his greatest ambition is to put small amounts of computing power into everyday items. Subramanian has devised radio frequency sensors that can be printed onto the plastic and paper that wrap fresh foods and packaged goods in stores. He's confident his University of California, Berkeley, group can produce the circuits for less than one cent each—compared with the current manufacturing cost of one dollar for a conventional radio frequency tag. Such tags on grocery items could give shoppers price and content information, even on-the-spot discounts. A sensor in a carton of milk could measure lactic-acid levels and signal when it's time for a fresh container. "I'm not looking to make the best and fastest electronic devices," Subramanian says. "I'm just making them good and fast enough so they can be placed everywhere in everything."

STEVE TUECKE | AGE 34

SOFTWARE

ARGONNE NATIONAL LABORATORY

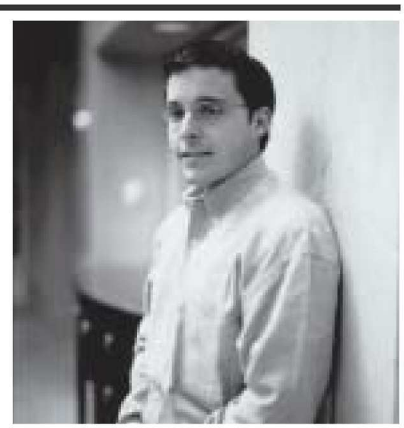
In 1995, Steve Tuecke's boss, Ian Foster, offered the organizers of a supercomputing convention a demonstration of "grid computing"—linking supercomputers at university and government labs into a single shared resource. The problem: the labs' computers had incompatible hardware, security arrangements and queuing procedures, and nobody had written a program to resolve them. "My first thought was 'Oh, jeez,'" says Tuecke, a software designer in Foster's Distributed Systems Lab in Argonne, IL. But within weeks, Tuecke had created the code. The demo was the talk of the convention. Tuecke's software grew into the Globus Toolkit—the "middleware" now used by hundreds of scientists worldwide to share high-end computers, databases and instruments remotely. Using Globus, a European Space Agency researcher could log into his desktop and run a climate simulation on a NASA supercomputer in California. Companies like Compaq, Fujitsu, IBM and Microsoft are eyeing Globus as a foundation for business-to-business Web services. "What the Web did for document sharing, the grid is doing for more general resource sharing," notes Tuecke, who recently became the lab's new software architect.

TIM TUTTLE | AGE 33

INTERNET AND WEB

BANG NETWORKS

When Tim Tuttle was 30, he quit his job at Lucent Technologies' Bell Labs, moved into a dilapidated apartment in Cambridge, MA, and began to reinvent the Web. It had a freshness problem. If the information on a Web page changes while you're reading it, you don't know—unless you hit the "refresh" button. Tuttle saw a different possibility: a virtual network, overlaying the Web, that lets sites send you live updates on information that changes, the moment it changes. And he was sure he could get it to function on ordinary Web browsers using ordinary Internet protocols—no extra software needed. Working with no funding or source of income, he built the first node of such a network: the prototype of the "Bang object router." After securing $10 million in July 2000, Tuttle, an active ultimate Frisbee player, moved to San Francisco to become an Internet entrepreneur. Six months later, his network was up and running, used chiefly by financial-services companies that need continually updated information from dozens of sources. Tuttle's company, Bang Networks, has thrived through the dot-com collapse: it raised almost half of its $32 million in November 2001.



TUTTLE: FURNALD/GRAY

TR100PROFILES

CAMILLE UTTERBACK | AGE 31

ARTS

NEW YORK UNIVERSITY

Media artist Camille Utterback's award-winning video tracking exhibits create spaces where computers follow and interact with a person's entire body. In *Text Rain*, a demonstration based on patent-pending software created by Utterback and artist Romy Achituv, participants see themselves projected in real time on a wall while letters from the lines of a poem rain on their bodies. As the people move, the letters adjust accordingly. In *Crossing*, what appears to be an abstract painting on the wall is really a projection that ripples in response to a viewer's movements. Utterback's goal, both as an artist and an assistant professor at New York University and the Parsons School of Design, is to "help people realize that when technology systems are designed well, they are really fun." Utterback, who in November 2000 started her own company, Creative Nerve, is a rare example of a computer programmer trained in the fine arts. Carl Goodman, curator of digital media at the American Museum of the Moving Image, says Utterback excels at following her curiosity and that her work "will stand up to scrutiny in the future, when the technology she's using will no longer be novel."

LES WELCH | AGE 32

TRANSPORTATION

LOCKHEED MARTIN

Les Welch has been fixing equipment ever since his bike broke in sixth grade. At aerospace giant Lockheed Martin he fixes manufacturing. Welch is applying lean-production techniques pioneered for auto assembly to the manufacture of F-22 fighter planes, bucking the defense industry's history of inefficient production. Traditionally, aircraft have been built in one spot, with assembly workers walking many kilometers (this has been measured) to fetch thousands of tools and parts. In Welch's approach, a nascent aircraft will move from one work center to another, each designed to minimize worker movement and maximize assembly convenience. Inventory is also reduced. Eric Ouellette at Lockheed Martin says the changes will cut manufacturing time up to 40 percent. Ouellette, formerly Welch's senior manager, says Welch is "passionate about eliminating waste." Before earning his industrial engineering degree, Welch ran manufacturing for a large family business that made aluminum toolboxes for pickup trucks. As for his personal tinkering, it's now directed at his 1986 Jeep Grand Wagoneer.

SUSIE WEE | AGE 32

INTERNET AND WEB

HEWLETT-PACKARD LABORATORIES

Handheld wireless devices are great for voice and simple data but are frustratingly limited when it comes to handling video—mostly because today's networks were designed for wired computers with robust processors and full-sized screens. Susie Wee, R&D manager for Hewlett-Packard Laboratories' streaming media systems group—and an avid hockey player—is skating around those constraints. Her first move was to devise algorithms that adapt data-heavy video streams to the capabilities of different online computers. The result: a handheld device can receive video at a lower resolution than a workstation, allowing it to display the video much faster. Wee is now developing protocols for moving streamed content away from central Internet servers to cache servers geographically closer to end users. Doing so would reduce network congestion and interruptions, making video and audio flow more easily to wireless devices. Wee's goal is to turn your cell phone into a full-blown multimedia player—a goal she is speeding toward.

CHRISTOPH WESTPHAL | AGE 33

BIOTECHNOLOGY

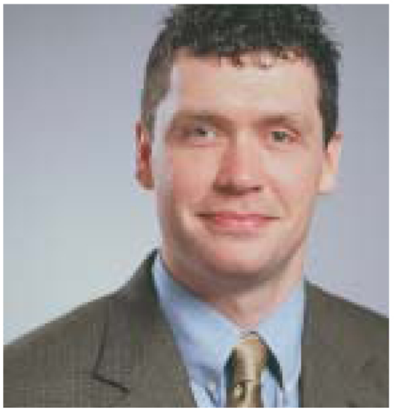
POLARIS VENTURE PARTNERS

Christoph Westphal invents startups. He restlessly searches for scientific advances he can transform into practical technologies. After grabbing an MD and PhD at Harvard in a mere six years, Westphal did a two-year stint at consultancy McKinsey, where he designed business development strategies for high-tech firms. He jumped to Waltham, MA-based Polaris Venture Partners in 2000 and is now a general partner advising five startups, one of which he cofounded. Westphal brings more than cash to the table: just ask the people at MIT spinoff Mimeon, in Cambridge, MA. Robert Langer, a prolific MIT inventor, says Mimeon was launched in 2001 after Westphal asked him "penetrating questions" about the underexploited potential of carbohydrate therapeutics. Langer introduced Westphal to MIT bioengineer Ram Sasisekharan and his technology for sequencing complex carbohydrates. Within months, Westphal brought in other scientific experts as well as $2 million in seed money. Mimeon is now zeroing in on its first target: an improved version of the blood thinner heparin—a substance derived from hog intestines that generates $2 billion in sales annually.

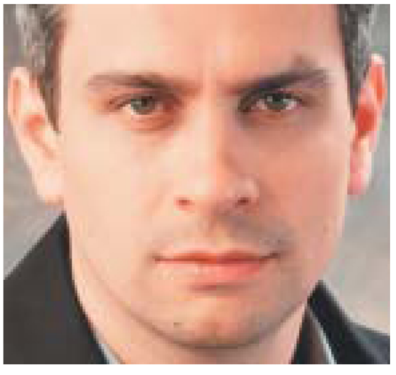
SEAN WILLEMS | AGE 29

SOFTWARE

BOSTON UNIVERSITY



Sean Willems's quest for simplicity dates back to childhood; he recalls being "stressed that 'Kansas' and 'Arkansas' weren't pronounced the same way." Now the cofounder and chief scientist of Boston-based Optiant cuts through complexity as an industrial pioneer. Willems, who is also an assistant professor at Boston University, creates software that streamlines the flow of parts and materials to manufacturers. While a PhD candidate at MIT's Sloan School of Management, he wrote an algorithm that optimizes such supply chain flows so manufacturers can cut costs by paring inventory. Previous algorithms solved only pieces of the problem; Willems addressed the task in its entirety. Willems tested his theories with leaders like Hewlett-Packard and Nortel Networks. When he applied them in a division of Eastman Kodak, the company cut inventory levels by 40 percent and saved $10 million over two years. The "cool thing about the life I lead," he says, "is that I get to develop the theory at Boston University and apply it at Optiant."



NEIL YOUNG | AGE 31

ENTERTAINMENT

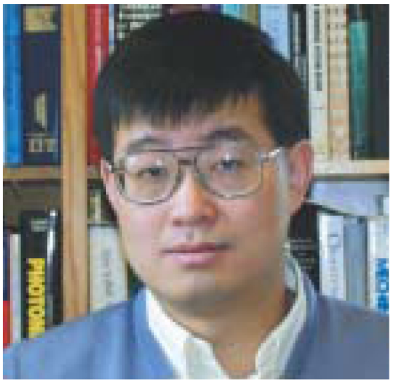
ELECTRONIC ARTS

You pick up your phone and an unfamiliar computer-generated voice threatens you. Strangers send you cryptic faxes and chilling e-mails about government conspiracy. But it's all part of the online game Majestic, created by Neil Young. After stints as a teenage programmer in the United Kingdom and, later, at Virgin Interactive in the United States, Young helped launch Redwood City, CA-based Electronic Arts' landmark Ultima Online role-playing game in 1997. Believing the potential of Internet games wasn't being fully explored, he then got restless. He wanted people to play games with media they used every day: the Web, e-mail, faxes, instant messages and phone calls. When Electronic Arts launched Majestic in July 2001, thousands of players paid $9.99 a month to take part. After September 11, Majestic shut down for a week and usage declined, forcing the company to wrap up the game in April 2002. Young is now developing an adaptation of *The Lord of the Rings* for the Xbox, the GameCube and other systems. Once again, he's thinking outside the box: "It's not a running, jumping, shooting game," he warns.

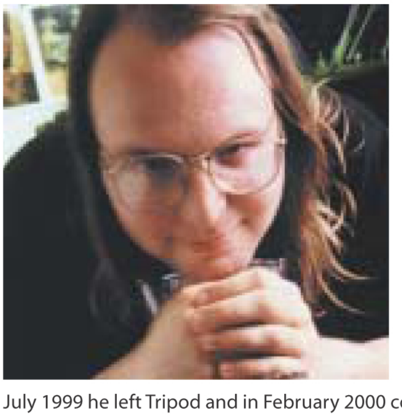
JUN YE | AGE 34

NANOTECHNOLOGY

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY



Jun Ye is a laser Jedi, wielding beams so precise they are destined to become a nanotech force. The Shanghai-born physicist came to the United States for grad school in 1989, yearning for theoretical work. But the laser lab lured him, and he set about tightening the precision of its instruments—to brilliant effect. By 2001, Ye had produced a stream of photons with timing steadier than the oscillations of an atomic clock. Last year, he synchronized and phase-tracked two pulsating beams of different colors so closely that they melded into one coherent beam—a feat physicists had thought impossible. Ye's phase-locked pulses can be shaped and shortened when different lasers are added to the mix. University of Colorado physicist Carl Wieman, whose atom-trapping laser tricks earned him a Nobel Prize last year, says Ye's tunability gives nanotechnologists a new tool for simultaneously tweaking each bond in intricate molecules. Ye is now refining his tools to push the frontiers of a variety of fields. With pulses fast enough, Ye figures he can talk to an atom's electrons.



ETHAN ZUCKERMAN | AGE 28

INTERNET AND WEB

GEEKCORPS

When Ethan Zuckerman went to Ghana in 1993 as a Fulbright scholar in percussion, he immediately tried to get online; he was a Usenet junkie and eager to e-mail his girlfriend (now his wife). But in bustling Accra, he found only one temperamental Net connection. Zuckerman later became vice president of R&D at Web-hosting company Tripod, which made him a dot-com millionaire, but he never forgot Ghana's inadequate communications. In July 1999 he left Tripod and in February 2000 cofounded Geekcorps in North Adams, MA. Geekcorps sends volunteers with information technology expertise to underdeveloped countries for four-month stints, where they help businesses—from furniture factories to radio stations—get online, expand sales and thus create jobs. One volunteer even helped launch the Ghanaian parliament's Web sites. Funded by foundations, aid agencies and private donors, Geekcorps has sent 35 tutors to Ghana and several other countries. A recent merger with the International Executive Service Corps gives Zuckerman the support to expand much further. There's no shortage of volunteers; more than 1,100 people are on Geekcorps's waiting list.

COURTESY OF AKAMAI TECHNOLOGIES

DANIEL LEWIN

1970-2001

INTERNET AND WEB

AKAMAI TECHNOLOGIES

For the 850 employees at Akamai Technologies, Sept. 11, 2001, was a day of agony and achievement. At 10:00 a.m., American Airlines confirmed that Daniel Lewin, the company's cofounder and chief technology officer, was aboard Flight 11, the first plane terrorists crashed into the World Trade Center. Akamai was built on Lewin's groundbreaking computer algorithms—the very ones that prevented the Internet from choking that day.

Born in Denver, Lewin emigrated to Israel with his family in 1983. He served four years in the Israel Defense Forces, then completed computer science and mathematics degrees at Technion University, while working at IBM in Haifa. In 1996 Lewin enrolled at MIT to pursue a master's degree. The growing World Wide Web was threatening to cause massive Internet congestion, and mathematics professor Tom Leighton drafted Lewin to help tackle the problem.

Lewin's master's thesis proposed a solution. At the time, a Web server in Atlanta—say, CNN's—would have routed its Web pages through numerous networks to reach a computer in Seattle. But if duplicate pages were maintained on servers around the world, they could be delivered faster and more directly, with less chance of interruption. Lewin's algorithms were designed to let servers monitor traffic over the networks and then determine which of them could deliver a desired page most efficiently.

Lewin, Leighton and MBA Jonathan Seelig started Akamai in Cambridge, MA, in August 1998 to commercialize Lewin's algorithms. Seelig, now vice president, says Lewin was energized by the startup. He had an affinity for speed and freedom, demonstrated by his love of motorcycles, sports cars and skiing. Akamai went public in 1999. Today, the $163 million company operates more than 13,500 servers in 66 countries. Some 1,200 clients, including CNN, Coca-Cola, MSNBC and Xerox, pay Akamai to route their Web pages quickly, freeing them from the need to expand server capacity to handle peak traffic.

Akamai's efficient routing has the added benefit of leveling the load across the Internet, preventing crippling bottlenecks. Immediately following Lewin's death, the world swarmed the Web for news of the terrorist attack. Akamai's grief-stricken employees watched as traffic spiked to four times its normal volume. The Internet held firm. "As the late-night hours came upon us and Web traffic eased," Seelig says, "we all realized that Danny's vision had been achieved. We only wish that Danny could have seen it." Lewin is survived by his wife, Anne, and two young sons.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TR100 LISTING BY AREA

TR100 CONTRIBUTORS

PROJECT EDITORS

Choosing 100 young innovators and profiling each and every one of them would be an all-hands-on-deck effort for any magazine. In fact, *Technology Review* needed many more hands than we actually had on our staff. Fortunately, we didn't need to look far for them. Mark Fischetti, who honchoed the whole project, is a known commodity in these parts. Mark has written for us before, most notably his excellent cover story "The Future of TV" in the November 2001 issue. Fischetti is used to working smoothly to get big projects organized, having edited special issues for other publications and worked with notables such as Michael Dertouzos and Tim Berners-Lee on their books. For the TR100, Mark helped us set up the panel of judges, obtained the judges' comments, and, his biggest task, assigned and edited the flood of profiles.

Mark did a lot, but he couldn't have finished the job without Brad Stenger. Brad has been through this process before; a Georgia Tech graduate student and an inveterate fan of innovators, he came to *TR* in the summer of 1999, when he offered himself up as a summer intern. His interests and talents were perfectly suited to the first TR100 project, and he spent that summer and fall identifying hundreds of candidates. He did much the same this time, as well as providing research on candidates, soliciting letters of recommendation, writing profiles and writing a story that follows a group of the first TR100 from then until now *(see "Where Are They Now?" p. 98)*. To Mark and Brad, and to all of those who contributed, we offer heartfelt thanks. *—The Editors*

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WHERE ARE THEY NOW?

IN NOVEMBER 1999, WE NAMED THE MEMBERS OF THE FIRST TR100. AND A REMARKABLE GROUP THEY WERE—BRILLIANT, CREATIVE AND OUT TO CHANGE THE WORLD. THEY STILL ARE.

BY BRAD STENGER
ILLUSTRATION BY GENE GREIF

For many of the 1999 TR100, commercialization of their innovations and scientific advances has been a primary concern over the last several years. It's been a challenging job, especially given the rapidly changing technology market. The dot-com mania, at its peak in 1999, has long since subsided; wireless and telecommunications markets are sluggish. But research in biotechnology, nanotechnology and information technology is exploding. And many of the original TR100 continue to show a remarkable ability to aggressively turn that research into real technologies.

Take **Peter Seeberger.** A professor of chemistry at MIT, Seeberger was chosen to the 1999 TR100 for his innovative work in the esoteric field of carbohydrate biochemistry. Then, at the awards ceremony, he met another young innovator, fellow honoree **Carmichael Roberts**, cofounder of Brighton, MA-based Surface Logix, a drug discovery startup. Their ensuing collaboration culminated in the formation of Ancora Pharmaceuticals to commercialize carbohydrate-based vaccines. This spring, Seeberger and an Australian biologist he met through Roberts are collaborating on groundbreaking research that could lead to the first effective vaccine against malaria, a disease that plagues five to 10 percent of the world's population, killing two million every year.

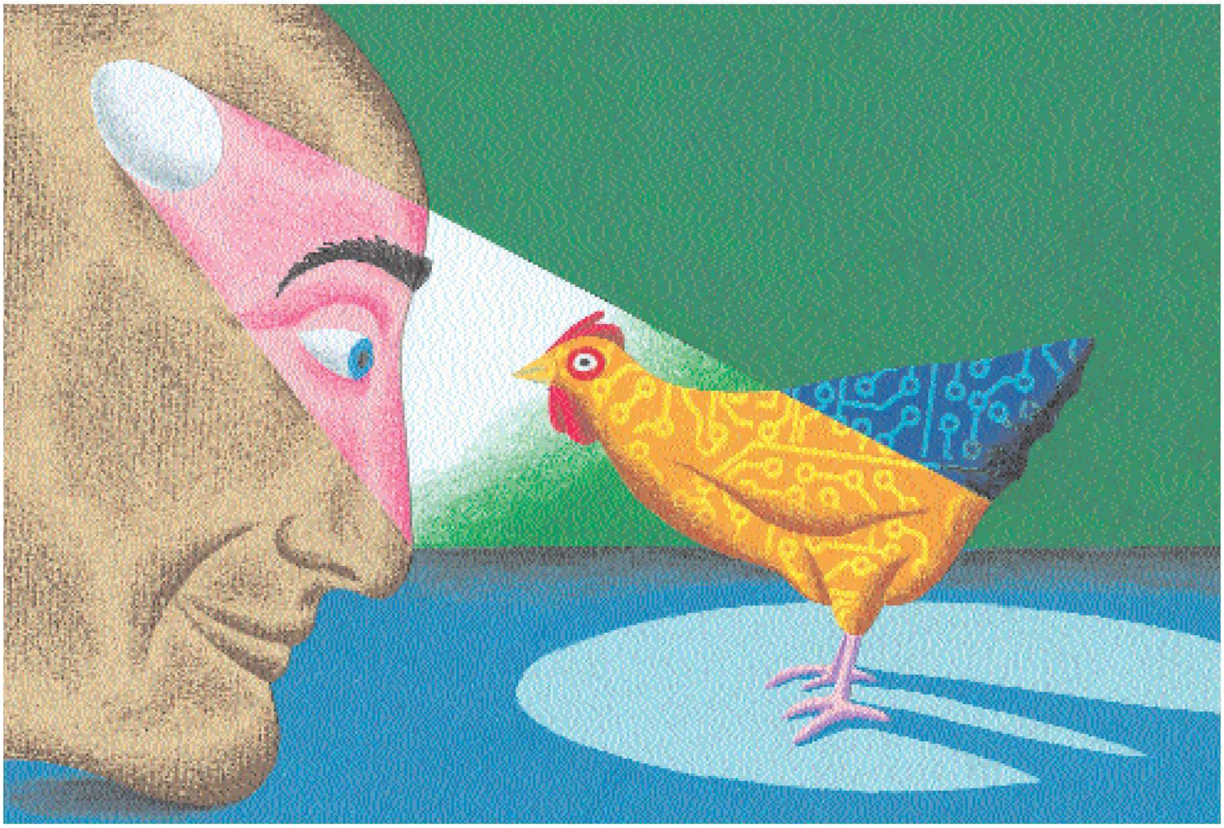
David Clemmer is another 1999 TR100 member who still has high ambitions. Last October, he shipped his life's work from his lab at Indiana University to Waltham, MA, and a small startup called Beyond Genomics, where he is a founding scientific advisor. The company is the first in a new discipline called systems biology, and Clemmer's invention, a novel lab instrument to automate the process of taking chemical snapshots of living cells, is the linchpin of its business plan. The goal: to better understand the biological processes behind human neurology and find a cure for diseases such as Alzheimer's and schizophrenia.

Tejal Desai, a researcher in tiny machines used for drug delivery and diagnostics, says "the TR100 raised the visibility" of her fledgling field. "Before that, no one was paying much attention." A rising star in the hot new field, Desai left the University of Illinois at Chicago in January 2002 to become an associate professor at Boston University. Meanwhile, Columbus, OH-based iMedd is working to commercialize an insulin release capsule that Desai developed; human tests are scheduled to begin soon.

Even for some named to the original TR100 for their innovations in information technology and the Internet, the growing opportunities in biotech have been too tempting to ignore. **Adam Beberg**, an expert in using networks of linked PCs for distributed computing, made his reputation breaking encryption codes. Now Beberg is using the same distributed-computing tools to help crack some of biotech's biggest problems: understanding how proteins fold into their final three-dimensional shapes and how genes code for proteins. Tens of thousands of PCs around the world, which together offer more computational power than supercomputers, are now joined in Folding@home and Genome@home, thanks to Beberg and his collaborators at Stanford University (including 2001 honoree Vijay Pande).

The Internet business has not exactly been smooth sailing during the last few years, but even in those rough waters, some TR100 members have managed to flourish. **Marc Andreessen**, for one, has not lost his magic touch. One of the founders of Netscape, Andreessen cofounded startup Loudcloud in September 1999 to outsource Internet services. In March 2001, Loudcloud went public and raised $150 million, braving a disastrous climate for Internet investments.

Others tied to the "new economy" haven't fared as well. In 1999, **Michael Saylor** and his company, MicroStrategy, were riding high. Saylor had a grand vision for his Internet software; he called it "query tone," and *TR*'s 1999 profile said it "would make it possible to answer any question you might have, in the form you want it, quickly and reliably." Unfortunately, there were a few financial questions that the company couldn't answer. In March 2000, MicroStrategy was forced to "restate" its recent financial records; as a result, the company's stock



price dropped 140 points in a day, losing 62 percent of its value. But Saylor has survived. The slimmed-down McLean, VA-based software company now thrives by selling data-mining software for corporations. "Two years ago, we were in several different lines of business," Saylor says. "Today we are in one."

For others, the Internet roller coaster has been a bit less dramatic. Open-source software guru **Miguel de Icaza** was named not only a member of the TR100 but also *TR*'s innovator of the year in 1999 for his leadership of GNOME, an effort to create an easy-to-use, open-source graphical interface for Linux. De Icaza cofounded Boston, MA-based Ximian in October 1999 to create software products for GNOME users and has continued carrying the open-source banner. Most notably, de Icaza has led an effort to develop Mono, an open-source alternative to Microsoft's .Net software for Web-based applications.

The Internet was not the only tech sector to suffer hard hits since the first TR100. Telecom and networking saw their prospects rise and fall. **Wim Sweldens** was one of the survivors, joining the management ranks at Lucent Technologies' Bell Labs. As a director of research, he's now playing a major role in managing what's arguably the world's most talented technical corps. That's not to say his own research days are over. During the last two years, Sweldens has continued to publish seminal work on compression algorithms.

In 1999, **Steven Jurvetson**, managing director of San Francisco-based Draper Fisher Jurvetson, was an outspoken proponent of e-commerce. Now he has turned his attention to nanotech, becoming chairman of the NanoBusiness Alliance and investing in several nanotech startups. "Nanotech represents the natural culmination of a number of technology trends," suggests Jurvetson.

Joseph Jacobson is one of those technologists out to prove Jurvetson right. In 1999, Jacobson was best known as cofounder of E Ink, a company commercializing paperlike electronic displays. Now Jacobson, director of the NanoMedia group at MIT's Media Lab, is well into his next project. His lab recently used radio waves and nanoscale antennae to control strands of DNA. Jacobson is optimistic that the technique can be used to improve disease diagnosis and drug delivery. In October 2000, he cofounded engeneOS in Waltham, MA, to develop the technology. Jacobson, a veteran when it comes to commercializing radical innovations, is under no illusions concerning what it takes to get products to market. "It's hard work. Instant success doesn't happen."

Erik Winfree, a Caltech professor who specializes in DNA computing, **Hideo Mabuchi**, a physicist at Caltech and pioneer in quantum computing, and **Daniel Schrag**, a geochemist at Harvard University, all won MacArthur Fellowships in 2000. The coveted "genius grants" give the researchers $500,000 each with "no strings attached" over five years.

Winfree, for one, reports that "progress is slow" in his efforts to learn how to use DNA molecules as the basic elements in computing. But then, no one said changing the world would be easy.

SCIENCE GOES MEDIEVAL

A few years back, I fretted in print that, given the mounting proprietary claims in some scientific fields, we risked entering a new kind of Dark Ages, replete with warring fiefdoms tightly guarding their knowledge. Okay, I admit the metaphor was a bit heavy handed. But with the "new economy" so obsessed with intellectual property, I could see just how frequently secrecy was replacing the collegial, open exchange of scientific information.

At the time, many mainstream pundits scoffed at my gloomy assessment. *BusinessWeek* wittily dubbed the idea "patent nonsense." (Boy, that stung!) Well, I'm sticking to my guns, especially after seeing the results of a survey of geneticists published earlier this year in the *Journal of the American Medical Association* (available for a fee at www.jama.ama-assn.org). I don't know what the *BusinessWeek* folks would say, but to my eye, the problem of secrecy looks worse than ever.

In this study, a team of researchers, led by Eric Campbell at Massachusetts General Hospital, surveyed 1,240 geneticists at 100 universities. Among the findings: Nearly three-quarters of the scientists (73 percent) report that the withholding of data among their colleagues is slowing progress in their field. Sixty-three percent say the situation is harming relationships with their peers. More than half hold that their colleagues' refusals to share data or materials have adversely affected research and the education of their students. In short, they are not a happy lot.

Some of the survey's specific findings are even more worrisome. Consider:

- 24 percent of geneticists say the lack of sharing in their field has caused them to abandon promising lines of research.
- 28 percent note that the decline in data sharing has prevented them from replicating published research. (Another stunner! Replication of results is a requisite for scientific progress.)

These findings are especially noteworthy because the robust exchange of information is a central tenet in science, where knowledge quite literally grows by being shared. It's a lot like the parable of the blind men who each approached a distinct part of an elephant and mistakenly believed the whole beast was like their own small portions. It's hard enough to grope your way in the dark; but it's virtually impossible to grasp the big picture without a whole lot of information-sharing. In science, an increase in secrecy is not just an unpleasant fact of life but a threat to the entire enterprise.

One astute observer, Robert Cook-Deegan, director of the National Cancer Policy Board, maintains that two primary factors influence the pace of innovation: the level of resource deployment (mainly funding) and the speed of information flow. I'm convinced he's right. High-tech analysts track closely where the money's going and who is getting patents. But maybe we ought to pay more attention to the rate of information exchange. That's what Eric Campbell and his team have essentially done in genetics—and the results should give us all pause.

In addition to slowing innovation, scientific secrecy also has an ethical dimension. Steven A. Rosenberg, chief of surgery at the National Cancer Institute, has complained about secrecy in biomedicine for years. Rosenberg tells the sad tale of the 17th-century Chamberlen brothers who developed the obstetrical forceps—of great value in difficult childbirths—but then kept the device secret within their practice. The brothers grew rich and famous while women and children throughout Europe—who could have been saved—died in childbirth. Three generations later, the Chamberlen family sold their secret and it became widely known. But few would claim their secrecy was ethically justifiable.

Nearly three-quarters of geneticists surveyed say the withholding of data is slowing progress in their field. This increase in secrecy is not only unpleasant, it is a threat to the entire enterprise.

To many, modern genetics is not so different. We're already seeing a similar kind of problem today, as high fees and proprietary rights have begun to stifle access to genetic tests like the one for predisposition to breast cancer *(see "Doctors without Patents,"* TR *December 2001)*. Responding to the new survey, Nelson Kiang, professor emeritus of physiology at MIT, notes that the trend toward greater secrecy "runs completely against the scientific ethos." As Kiang puts it, "A few people treat scientific work as a competitive sport. But our common enemy is ignorance, and we should be helping each other as fast as possible." Given this issue's importance, maybe we should insist that at least publicly funded research remain freely accessible to other scientists. The National Institutes of Health sensibly took a step in this direction with the Human Genome Project, requiring all NIH-funded researchers to publicly disclose their gene sequencing data within 24 hours of their discovery. But clearly, more needs to be done.

Which brings me back to the Dark Ages. Western civilization declined steadily during the 9th and 10th centuries. Why? As Joseph Strayer and Dana Munro explain in *The Middle Ages: 395-1500*, "Europeans seemed to have lost their ability to work together on a large scale." In genetics as on other high-tech frontiers, let's make sure we don't fall into the same trap. TR

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PEOPLE AND ORGANIZATIONS MENTIONED IN THIS ISSUE

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ORGANIZATIONS

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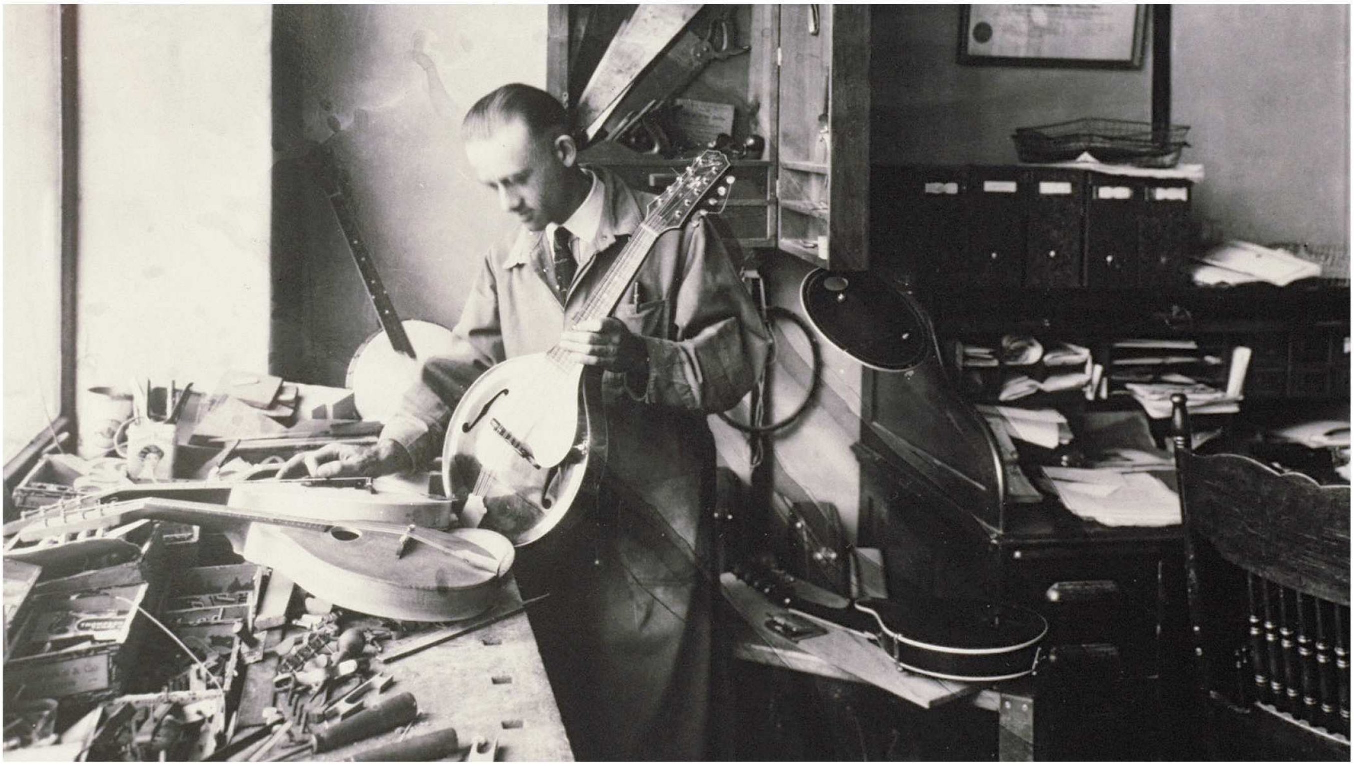

COURTESY OF GIBSON GUITAR

FOR THOSE ABOUT TO ROCK, WE SALUTE YOU

The first electric guitar flopped—but its legacy transformed popular music

Last year, nearly 900,000 electric guitars were sold in the United States, to professional musicians as well as those rowdy teenagers in the garage next door. The electric guitar's distinctive sound is now heard all over the radio, in nearly every genre of popular music, including rock, country, jazz and reggae. Electric-guitar technology, it turns out, goes back some 80 years—but almost blew a fuse on its way to market.

In 1923, Lloyd Loar *(above, with mandolin)* was an engineer at Gibson Guitar and bursting with inspiration. His revolutionary designs for stringed instruments are well known among aficionados; his Gibson F-5 mandolins, for example, are generally regarded as the best ever made. But Loar wasn't just interested in perfecting old designs; he was on the lookout for new ideas.

At the time, many guitarists complained that they could not be heard over other, louder instruments. To help solve this problem, Loar developed an electrostatic device that is the core of electric-guitar technology: the pickup. It detected vibrations in the soundboard of stringed instruments and converted them into electrical impulses; these impulses were then sent through an amplifier and out through a speaker as amplified sound. But Loar's bosses at Gibson weren't interested in his odd (but prescient) electric-instrument designs, and Loar left Gibson in 1924. He eventually formed a company to market his electric guitars, but the experimental nature of his designs made it difficult for him to get financing, and the firm went under. Another guitar designer, George Beauchamp, working with engineer Adolph Rickenbacker, who lent his name to the company they cofounded, patented a more refined electromagnetic pickup in the late 1930s. By then, several major guitar companies had created their own electric guitars, including Gibson.

It wasn't long before the new souped-up guitars stormed into popular music. Legendary jazz guitarist Charlie Christian popularized the electric guitar as a lead instrument when he played a 1936 Gibson ES-150 with the Benny Goodman Sextet. The electric guitar soon found its way into other genres, and by the 1950s, it was helping to create rock 'n' roll's distinctive sound. Guitarists Les Paul and, later, Jimi Hendrix used electric-guitar technology to create otherworldly sounds that weren't possible with unamplified guitars. What's the easiest way to gauge Loar's legacy? Just turn on MTV. TR

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Q&A
Mike Aguilar, President and COO, Panasonic Company National
HOW
Panasonic gets the big picture
What challenges were facing Panasonic? Well, digital products like DVD players and HDTVs are quickly replacing analog equipment, and it seems like every day new products with new features are being introduced. Our retailers gave us a wake-up call. They didn't want to be stuck with yesterday's products in inventory when their competition is selling today's, or even tomorrow's. They needed our assistance to reduce their inventories, our own inventory, and everyone's lead time.
How do you do all that? First you need total and real-time visibility across the value chain – to know exactly what's happening when it's happening, from logistics to production, on dealer shelves and suppliers' shelves, across North America and Japan. But more than just having it, that information must work dynamically within a planning and execution process. We achieve all that with i2's Supply Chain Management solution. It gives us real-time, point-of-sale information, even forward visibility into retailers' ad planning schedules and in-store promotion plans. Real collaboration is so much easier when everyone in the value chain has a true picture of customer demand and ways to quickly act on it.
Panasonic
What returns have you experienced with i2? Increased visibility and the ability to act on it deliver tremendous, measurable returns in value. Over the next 12 to 18 months, dynamic value chain management will help us plan future production to hit true demand. We've increased on-time delivery to 84% for major customers and lead our industry with a 90% in-stock rate. Customers have noticed, awarding us higher satisfaction ratings than ever. That means more sales from current customers and higher loyalty. We're not just suppliers and they're not just customers anymore. We're partners.
"Increased visibility and the ability to act on it deliver tremendous, measurable returns in value."
Why did you select i2? Other supply chain solutions consist of isolated products that don't communicate with other modules in the system. We didn't want to get into the old-style legacy systems where we had to patch everything together and hope that it all worked. i2 was offering us a unified solution in which all the separate modules talk together. That's the only way to truly manage the entire chain.
i2 is the value company, already $29.9 billion toward its goal of delivering $75 billion in audited value to its customers by 2005. For more information on i2 solutions for managing your dynamic value chain, visit www.i2.com or call 1-866-288-4896.
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